US011426095B2

(12) United States Patent
Walker et al.

(10) Patent No.: US 11,426,095 B2
(45) Date of Patent: Aug. 30, 2022

(54) FLEXIBLE INSTRUMENT LOCALIZATION FROM BOTH REMOTE AND ELONGATION SENSORS

(71) Applicant: **Auris Health, Inc.**, Redwood City, CA (US)

(72) Inventors: **Sean Walker**, Fremont, CA (US); **Dave Camarillo**, Aptos, CA (US); **Matt Roelle**, Sunnyvale, CA (US); **Christopher Sewell**, Sunnyvale, CA (US); **Aditya Koolwal**, San Francisco, CA (US)

(73) Assignee: **Auris Health, Inc.**, Redwood City, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1016 days.

(21) Appl. No.: **15/056,652**

(22) Filed: **Feb. 29, 2016**

(65) **Prior Publication Data**

US 2016/0228032 A1 Aug. 11, 2016

Related U.S. Application Data

(63) Continuation of application No. 13/833,733, filed on Mar. 15, 2013, now Pat. No. 9,271,663.

(51) **Int. Cl.**
A61B 5/06 (2006.01)
A61B 34/20 (2016.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61B 5/061*** (2013.01); ***A61B 5/0071*** (2013.01); ***A61B 5/7225*** (2013.01); ***A61B 34/20*** (2016.02);
(Continued)

(58) **Field of Classification Search**
CPC A61B 5/061; A61B 5/062; A61B 2034/2051; A61B 2034/2059;
(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,745,908 A 5/1988 Wardle
5,273,025 A 12/1993 Sakiyam et al.
(Continued)

FOREIGN PATENT DOCUMENTS

CN 101147676 3/2008
CN 101222882 7/2008
(Continued)

OTHER PUBLICATIONS

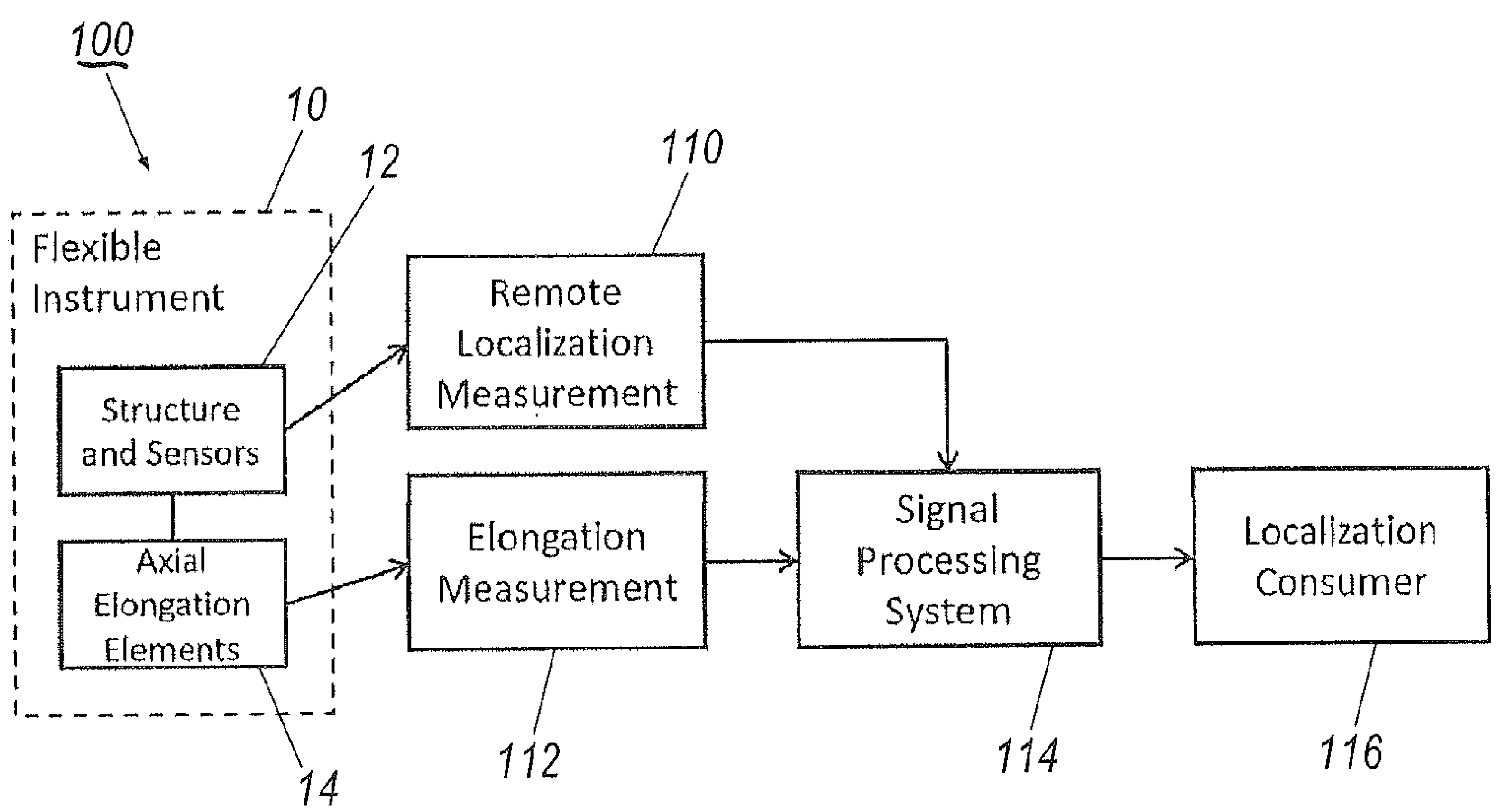
Wilson et al., "A Buyer's Guide to Electromagnetic Tracking Systems for Clinical Applications" Medical Imaging 2008: Visualization, Image-guided Procedures and Modeling Proc. of SPIE vol. 6918, 69182B, (2008) (Year: 2008).*
(Continued)

Primary Examiner — Colin T. Sakamoto
(74) *Attorney, Agent, or Firm* — Frost Brown Todd LLC

(57) **ABSTRACT**

A system and method of tracking a flexible elongate instrument within a patient is disclosed herein. The system is configured to obtain remote localization measurement data of the flexible elongate instrument and obtain elongation measurement data of the flexible elongate instrument. This data is combined and transformed to a coordinate reference frame to produce a localization of the flexible elongate instrument that is more accurate than the remote localization measurements or elongation measurement data alone. The combined localization is then provided to a localization consumer.

19 Claims, 8 Drawing Sheets



(51) **Int. Cl.**
A61B 5/00 (2006.01)
A61B 6/12 (2006.01)

(52) **U.S. Cl.**
CPC *A61B 5/062* (2013.01); *A61B 2034/2051* (2016.02); *A61B 2034/2061* (2016.02); *A61B 2034/2065* (2016.02)

(58) **Field of Classification Search**
CPC A61B 2034/2061; A61B 2034/2063; A61B 2034/2065
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,398,691	A	3/1995	Martin et al.
5,408,409	A	4/1995	Glassman et al.
5,524,180	A	6/1996	Wang et al.
5,526,812	A	6/1996	Dumoulin et al.
5,550,953	A	8/1996	Seraji
5,553,611	A	9/1996	Budd et al.
5,558,091	A	9/1996	Acker et al.
5,631,973	A	5/1997	Green
5,636,255	A	6/1997	Ellis
5,713,946	A	2/1998	Ben-Haim
5,729,129	A	3/1998	Acker
5,749,362	A	5/1998	Funda et al.
5,831,614	A	11/1998	Tognazzini et al.
5,859,934	A	1/1999	Green
5,873,822	A	2/1999	Ferre et al.
5,876,325	A	3/1999	Mizuno et al.
5,902,239	A	5/1999	Buurman
5,920,319	A	7/1999	Vining et al.
5,935,075	A	8/1999	Casscells
5,951,475	A	9/1999	Gueziec et al.
6,016,439	A	1/2000	Acker
6,019,724	A	2/2000	Gronningsaeter et al.
6,038,467	A	3/2000	De Bliek et al.
6,047,080	A	4/2000	Chen
6,059,718	A	5/2000	Taniguchi et al.
6,063,095	A	5/2000	Wang et al.
6,167,292	A	12/2000	Badano
6,203,493	B1	3/2001	Ben-Haim
6,226,543	B1	5/2001	Gilboa et al.
6,233,476	B1	5/2001	Strommer et al.
6,246,784	B1	6/2001	Summers
6,246,898	B1	6/2001	Vesely
6,253,770	B1	7/2001	Acker et al.
6,259,806	B1	7/2001	Green
6,272,371	B1	8/2001	Shlomo
6,332,089	B1	12/2001	Acker
6,424,885	B1	7/2002	Niemeyer et al.
6,425,865	B1	7/2002	Salcudean et al.
6,466,198	B1	10/2002	Feinstein
6,490,467	B1	12/2002	Bucholz
6,553,251	B1	4/2003	Lahdesmaki
6,592,520	B1	7/2003	Peszynski
6,593,884	B1	7/2003	Gilboa et al.
6,665,554	B1	12/2003	Charles
6,690,963	B2	2/2004	Ben-Haim
6,690,964	B2	2/2004	Beiger et al.
6,711,429	B1	3/2004	Gilboa et al.
6,726,675	B1	4/2004	Beyar
6,782,287	B2	8/2004	Grzeszczuk et al.
6,812,842	B2	11/2004	Dimmer
6,892,090	B2	5/2005	Verard et al.
6,899,672	B2	5/2005	Chin
6,926,709	B2	8/2005	Beiger et al.
6,994,094	B2	2/2006	Schwartz
6,996,430	B1	2/2006	Gilboa et al.
7,155,315	B2	12/2006	Niemeyer et al.
7,180,976	B2	2/2007	Wink
7,206,627	B2	4/2007	Abovitz
7,233,820	B2	6/2007	Gilboa
7,386,339	B2	6/2008	Strommer et al.
7,756,563	B2	7/2010	Higgins
7,850,642	B2	12/2010	Moll et al.
7,901,348	B2	3/2011	Soper
8,052,621	B2	11/2011	Wallace et al.
8,092,397	B2	1/2012	Wallace et al.
8,155,403	B2	4/2012	Tschirren
8,190,238	B2	5/2012	Moll et al.
8,298,135	B2	10/2012	Ito et al.
8,317,746	B2	11/2012	Sewell et al.
8,388,556	B2	3/2013	Wallace et al.
8,394,054	B2	3/2013	Wallace et al.
8,460,236	B2	6/2013	Roelle et al.
8,657,781	B2	2/2014	Sewell et al.
8,672,837	B2	3/2014	Roelle et al.
8,821,376	B2	9/2014	Tolkowsky
8,858,424	B2	10/2014	Hasegawa
8,929,631	B2	1/2015	Pfister et al.
9,014,851	B2	4/2015	Wong et al.
9,039,685	B2	5/2015	Larkin et al.
9,057,600	B2	6/2015	Walker et al.
9,125,639	B2	9/2015	Mathis
9,138,129	B2	9/2015	Diolaiti
9,173,713	B2	11/2015	Hart et al.
9,183,354	B2	11/2015	Baker et al.
9,186,046	B2	11/2015	Ramamurthy et al.
9,271,663	B2	3/2016	Walker et al.
9,272,416	B2	3/2016	Hourtash et al.
9,283,046	B2	3/2016	Walker et al.
9,289,578	B2	3/2016	Walker et al.
9,459,087	B2	10/2016	Dunbar
9,498,291	B2	11/2016	Balaji et al.
9,498,601	B2	11/2016	Tanner et al.
9,504,604	B2	11/2016	Alvarez
9,532,840	B2	1/2017	Wong et al.
9,561,083	B2	2/2017	Yu et al.
9,566,414	B2	2/2017	Wong et al.
9,603,668	B2	3/2017	Weingarten et al.
9,622,827	B2	4/2017	Yu et al.
9,629,595	B2	4/2017	Walker et al.
9,629,682	B2	4/2017	Wallace et al.
9,636,184	B2	5/2017	Lee et al.
9,710,921	B2	7/2017	Wong et al.
9,713,509	B2	7/2017	Schuh et al.
9,717,563	B2	8/2017	Tognaccini
9,726,476	B2	8/2017	Ramamurthy et al.
9,727,963	B2	8/2017	Mintz et al.
9,737,371	B2	8/2017	Romo et al.
9,737,373	B2	8/2017	Schuh
9,744,335	B2	8/2017	Jiang
9,763,741	B2	9/2017	Alvarez et al.
9,788,910	B2	10/2017	Schuh
9,818,681	B2	11/2017	Machida
9,827,061	B2	11/2017	Balaji et al.
9,844,353	B2	12/2017	Walker et al.
9,844,412	B2	12/2017	Bogusky et al.
9,867,635	B2	1/2018	Alvarez et al.
9,918,681	B2	3/2018	Wallace et al.
9,931,025	B1	4/2018	Graetzel et al.
9,949,749	B2	4/2018	Noonan et al.
9,955,986	B2	5/2018	Shah
9,962,228	B2	5/2018	Schuh et al.
9,980,785	B2	5/2018	Schuh
9,993,313	B2	6/2018	Schuh et al.
10,016,900	B1	7/2018	Meyer et al.
10,022,192	B1	7/2018	Ummalaneni
10,123,755	B2	11/2018	Walker et al.
10,130,427	B2	11/2018	Tanner et al.
10,136,950	B2	11/2018	Schoenefeld
10,145,747	B1	12/2018	Lin et al.
10,159,532	B1	12/2018	Ummalaneni et al.
10,278,778	B2	5/2019	State
10,299,870	B2	5/2019	Connolly et al.
10,482,599	B2	11/2019	Mintz et al.
10,517,692	B2	12/2019	Eyre et al.
10,524,866	B2	1/2020	Srinivasan
10,639,114	B2	5/2020	Schuh
10,667,875	B2	6/2020	DeFonzo
10,743,751	B2	8/2020	Landey et al.
10,751,140	B2	8/2020	Wallace et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

10,765,303 B2 9/2020 Graetzel et al.
10,765,487 B2 9/2020 Ho
2001/0021843 A1 9/2001 Bosselmann et al.
2001/0039421 A1 11/2001 Heilbrun
2002/0065455 A1 5/2002 Ben-Haim et al.
2002/0077533 A1 6/2002 Bieger et al.
2002/0120188 A1 8/2002 Brock et al.
2003/0105603 A1 6/2003 Hardesty
2003/0125622 A1 7/2003 Schweikard
2003/0135204 A1* 7/2003 Lee A61B 90/36 606/1
2003/0181809 A1 9/2003 Hall et al.
2003/0195664 A1 10/2003 Nowlin et al.
2004/0047044 A1 3/2004 Dalton
2004/0072066 A1 4/2004 Cho et al.
2004/0186349 A1 9/2004 Ewers
2004/0249267 A1 12/2004 Gilboa
2004/0263535 A1 12/2004 Birkenbach et al.
2005/0004516 A1 1/2005 Vanney
2005/0027397 A1 2/2005 Niemeyer
2005/0033149 A1 2/2005 Strommer et al.
2005/0060006 A1 3/2005 Pflueger
2005/0085714 A1 4/2005 Foley et al.
2005/0107679 A1 5/2005 Geiger
2005/0143649 A1 6/2005 Minai et al.
2005/0143655 A1 6/2005 Satoh
2005/0171508 A1 8/2005 Gilboa
2005/0182295 A1 8/2005 Soper et al.
2005/0193451 A1 9/2005 Quistgaard et al.
2005/0256398 A1 11/2005 Hastings
2005/0272975 A1 12/2005 McWeeney et al.
2006/0004286 A1 1/2006 Chang
2006/0015096 A1 1/2006 Hauck et al.
2006/0025668 A1 2/2006 Peterson
2006/0025676 A1 2/2006 Viswanathan et al.
2006/0058643 A1 3/2006 Florent
2006/0076023 A1 4/2006 Rapacki et al.
2006/0084860 A1 4/2006 Geiger
2006/0095066 A1 5/2006 Chang
2006/0098851 A1 5/2006 Shoham
2006/0149134 A1 7/2006 Soper et al.
2006/0173290 A1 8/2006 Lavallee et al.
2006/0184016 A1 8/2006 Glossop
2006/0209019 A1 9/2006 Hu
2006/0258935 A1 11/2006 Pile-Spellman et al.
2006/0258938 A1 11/2006 Hoffman et al.
2007/0015997 A1 1/2007 Higgins et al.
2007/0032826 A1 2/2007 Schwartz
2007/0055128 A1 3/2007 Glossop
2007/0055144 A1 3/2007 Neustadter
2007/0073136 A1 3/2007 Metzger
2007/0083193 A1 4/2007 Werneth
2007/0123748 A1 5/2007 Meglan
2007/0135886 A1 6/2007 Maschke
2007/0156019 A1 7/2007 Larkin et al.
2007/0167743 A1 7/2007 Honda
2007/0167801 A1 7/2007 Webler et al.
2007/0208252 A1 9/2007 Makower
2007/0225559 A1 9/2007 Clerc et al.
2007/0249901 A1 10/2007 Ohline et al.
2007/0253599 A1 11/2007 White et al.
2007/0269001 A1 11/2007 Maschke
2007/0276180 A1 11/2007 Greenburg et al.
2007/0287992 A1* 12/2007 Diolaiti A61B 34/37 606/1
2007/0293721 A1 12/2007 Gilboa
2007/0299353 A1 12/2007 Harlev et al.
2008/0071140 A1 3/2008 Gattani
2008/0079421 A1 4/2008 Jensen
2008/0103389 A1 5/2008 Begelman et al.
2008/0118118 A1 5/2008 Berger
2008/0118135 A1 5/2008 Averbach
2008/0123921 A1 5/2008 Gielen et al.
2008/0147089 A1 6/2008 Loh
2008/0161681 A1 7/2008 Hauck
2008/0183064 A1 7/2008 Chandonnet
2008/0183068 A1 7/2008 Carls et al.
2008/0183073 A1 7/2008 Higgins et al.
2008/0183188 A1 7/2008 Carls et al.
2008/0201016 A1 8/2008 Finlay
2008/0207997 A1 8/2008 Higgins et al.
2008/0212082 A1 9/2008 Froggatt et al.
2008/0218770 A1 9/2008 Moll et al.
2008/0243142 A1 10/2008 Gildenberg
2008/0262297 A1 10/2008 Gilboa
2008/0275349 A1 11/2008 Halperin
2008/0287963 A1 11/2008 Rogers et al.
2008/0306490 A1 12/2008 Lakin et al.
2008/0312501 A1 12/2008 Hasegawa et al.
2009/0030307 A1 1/2009 Govari
2009/0054729 A1 2/2009 Mori
2009/0076476 A1 3/2009 Barbagli et al.
2009/0149867 A1 6/2009 Glozman
2009/0227861 A1 9/2009 Ganatra
2009/0248036 A1 10/2009 Hoffman et al.
2009/0259230 A1 10/2009 Khadem
2009/0262109 A1 10/2009 Markowitz et al.
2009/0292166 A1 11/2009 Ito
2009/0295797 A1 12/2009 Sakaguchi
2010/0008555 A1 1/2010 Trumer
2010/0039506 A1 2/2010 Sarvestani et al.
2010/0041949 A1 2/2010 Tolkowsky
2010/0054536 A1 3/2010 Huang
2010/0113852 A1 5/2010 Sydora
2010/0121139 A1 5/2010 OuYang
2010/0160733 A1 6/2010 Gilboa
2010/0161022 A1 6/2010 Toikowsky
2010/0161129 A1 6/2010 Costa et al.
2010/0225209 A1 9/2010 Goldberg
2010/0240989 A1 9/2010 Stoianovici
2010/0290530 A1 11/2010 Huang et al.
2010/0292565 A1 11/2010 Meyer
2010/0298641 A1 11/2010 Tanaka
2010/0328455 A1 12/2010 Nam et al.
2011/0054303 A1 3/2011 Barrick
2011/0092808 A1 4/2011 Shachar
2011/0113852 A1* 5/2011 Prisco G01B 11/18 73/1.15
2011/0184238 A1 7/2011 Higgins
2011/0234780 A1 9/2011 Ito
2011/0238082 A1 9/2011 Wenderow
2011/0245665 A1 10/2011 Nentwick
2011/0248987 A1 10/2011 Mitchell
2011/0249016 A1 10/2011 Zhang
2011/0276179 A1 11/2011 Banks et al.
2011/0295247 A1 12/2011 Schlesinger et al.
2011/0295267 A1 12/2011 Tanner et al.
2011/0295268 A1 12/2011 Roelle et al.
2011/0319815 A1 12/2011 Roelle et al.
2011/0319910 A1* 12/2011 Roelle A61B 34/71 606/130
2012/0046521 A1 2/2012 Hunter et al.
2012/0056986 A1 3/2012 Popovic
2012/0062714 A1 3/2012 Liu
2012/0065481 A1 3/2012 Hunter
2012/0069167 A1 3/2012 Liu et al.
2012/0071782 A1 3/2012 Patil et al.
2012/0082351 A1 4/2012 Higgins
2012/0116253 A1 5/2012 Wallace et al.
2012/0120305 A1 5/2012 Takahashi
2012/0165656 A1 6/2012 Montag
2012/0191079 A1 7/2012 Moll et al.
2012/0209069 A1 8/2012 Popovic
2012/0215094 A1 8/2012 Rahimian et al.
2012/0219185 A1 8/2012 Hu
2012/0289777 A1 11/2012 Chopra
2012/0289783 A1 11/2012 Duindam et al.
2012/0302869 A1 11/2012 Koyrakh
2013/0060146 A1 3/2013 Yang et al.
2013/0072787 A1* 3/2013 Wallace A61B 8/4254 600/424
2013/0096377 A1* 4/2013 Duindam A61B 10/04 600/104
2013/0144116 A1 6/2013 Cooper et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2013/0165945	A9	6/2013	Roelle
2013/0204124	A1	8/2013	Duindam
2013/0225942	A1	8/2013	Holsing
2013/0243153	A1	9/2013	Sra
2013/0246334	A1	9/2013	Ahuja
2013/0259315	A1	10/2013	Angot et al.
2013/0303892	A1	11/2013	Zhao
2013/0345718	A1	12/2013	Crawford
2014/0058406	A1	2/2014	Tsekos
2014/0107390	A1	4/2014	Brown
2014/0114180	A1	4/2014	Jain
2014/0148808	A1	4/2014	Inkpen et al.
2014/0142591	A1	5/2014	Alvarez et al.
2014/0148673	A1	5/2014	Bogusky
2014/0180063	A1	6/2014	Zhao
2014/0235943	A1	8/2014	Paris
2014/0243849	A1	8/2014	Saglam
2014/0257334	A1	9/2014	Wong et al.
2014/0257746	A1	9/2014	Dunbar et al.
2014/0264081	A1	9/2014	Walker et al.
2014/0275985	A1	9/2014	Walker et al.
2014/0275988	A1	9/2014	Walker et al.
2014/0276033	A1	9/2014	Brannan
2014/0276392	A1	9/2014	Wong et al.
2014/0276394	A1	9/2014	Wong et al.
2014/0276594	A1	9/2014	Tanner et al.
2014/0276646	A1	9/2014	Wong et al.
2014/0276934	A1	9/2014	Balaji et al.
2014/0276937	A1	9/2014	Wong et al.
2014/0277747	A1	9/2014	Walker et al.
2014/0296655	A1	10/2014	Akhbardeh et al.
2014/0309527	A1	10/2014	Namati et al.
2014/0309649	A1	10/2014	Alvarez et al.
2014/0343416	A1	11/2014	Panescu
2014/0350391	A1	11/2014	Prisco et al.
2014/0357953	A1	12/2014	Roelle et al.
2014/0357984	A1	12/2014	Wallace et al.
2014/0364739	A1	12/2014	Liu
2014/0364870	A1	12/2014	Alvarez et al.
2014/0379000	A1	12/2014	Romo et al.
2015/0051482	A1	2/2015	Liu et al.
2015/0051592	A1	2/2015	Kintz
2015/0054929	A1	2/2015	Ito et al.
2015/0057498	A1	2/2015	Akimoto
2015/0073266	A1	3/2015	Brannan
2015/0101442	A1	4/2015	Romo
2015/0112486	A1	4/2015	Larkin et al.
2015/0119638	A1	4/2015	Yu et al.
2015/0141808	A1	5/2015	Elhawary
2015/0141858	A1	5/2015	Razavi
2015/0142013	A1	5/2015	Tanner et al.
2015/0164594	A1	6/2015	Romo et al.
2015/0164596	A1	6/2015	Romo
2015/0223725	A1	8/2015	Engel
2015/0223765	A1	8/2015	Chopra
2015/0223897	A1	8/2015	Kostrzewski et al.
2015/0223902	A1	8/2015	Walker et al.
2015/0255782	A1	9/2015	Kim et al.
2015/0265087	A1	9/2015	Park
2015/0265359	A1	9/2015	Camarillo
2015/0265368	A1	9/2015	Chopra
2015/0265807	A1	9/2015	Park et al.
2015/0275986	A1	10/2015	Cooper
2015/0287192	A1	10/2015	Sasaki
2015/0297133	A1	10/2015	Jouanique-Dubuis et al.
2015/0297864	A1	10/2015	Kokish et al.
2015/0305650	A1	10/2015	Hunter
2015/0313503	A1	11/2015	Seibel et al.
2015/0335480	A1	11/2015	Alvarez et al.
2015/0374956	A1	12/2015	Bogusky
2015/0375399	A1	12/2015	Chiu et al.
2016/0000302	A1	1/2016	Brown
2016/0000414	A1	1/2016	Brown
2016/0000520	A1	1/2016	Lachmanovich
2016/0001038	A1	1/2016	Romo et al.
2016/0008033	A1	1/2016	Hawkins et al.
2016/0111192	A1	4/2016	Suzara
2016/0128992	A1	5/2016	Hudson
2016/0175059	A1	6/2016	Walker et al.
2016/0183841	A1	6/2016	Duindam et al.
2016/0199134	A1	7/2016	Brown et al.
2016/0202053	A1	7/2016	Walker et al.
2016/0206389	A1	7/2016	Miller
2016/0213432	A1	7/2016	Flexman
2016/0270865	A1	9/2016	Landey et al.
2016/0287279	A1	10/2016	Bovay et al.
2016/0287346	A1	10/2016	Hyodo et al.
2016/0296294	A1	10/2016	Moil et al.
2016/0314710	A1	10/2016	Jarc
2016/0331469	A1	11/2016	Hall et al.
2016/0360947	A1	12/2016	Iida
2016/0372743	A1	12/2016	Cho et al.
2016/0374541	A1	12/2016	Agrawal et al.
2017/0007337	A1	1/2017	Dan
2017/0055851	A1	3/2017	Al-All
2017/0065356	A1	3/2017	Balaji et al.
2017/0079725	A1	3/2017	Hoffman
2017/0079726	A1	3/2017	Hoffman
2017/0100084	A1	4/2017	Walker et al.
2017/0100199	A1	4/2017	Yu et al.
2017/0105803	A1	4/2017	Wong et al.
2017/0113019	A1	4/2017	Wong et al.
2017/0119413	A1	5/2017	Romo
2017/0119481	A1	5/2017	Romo et al.
2017/0119484	A1	5/2017	Tanner et al.
2017/0151027	A1	6/2017	Walker et al.
2017/0165011	A1	6/2017	Bovay et al.
2017/0172673	A1	6/2017	Yu et al.
2017/0189118	A1	7/2017	Chopra
2017/0202627	A1	7/2017	Sramek et al.
2017/0209073	A1	7/2017	Sramek et al.
2017/0209224	A1	7/2017	Walker et al.
2017/0215808	A1	8/2017	Shimol et al.
2017/0215969	A1	8/2017	Zhai et al.
2017/0238807	A9	8/2017	Veritkov et al.
2017/0258366	A1	9/2017	Tupin
2017/0290631	A1	10/2017	Lee et al.
2017/0296032	A1	10/2017	Li
2017/0296202	A1	10/2017	Brown
2017/0303941	A1	10/2017	Eisner
2017/0325896	A1	11/2017	Donhowe
2017/0333679	A1	11/2017	Jiang
2017/0340241	A1	11/2017	Yamada
2017/0340396	A1	11/2017	Romo et al.
2017/0348067	A1	12/2017	Krimsky
2017/0360418	A1	12/2017	Wong et al.
2017/0360508	A1	12/2017	Germain et al.
2017/0365055	A1	12/2017	Mintz et al.
2017/0367782	A1	12/2017	Schuh et al.
2018/0025666	A1	1/2018	Ho et al.
2018/0055582	A1	3/2018	Krimsky
2018/0098690	A1	4/2018	Iwaki
2018/0177383	A1	6/2018	Noonan et al.
2018/0177556	A1	6/2018	Noonan et al.
2018/0177561	A1	6/2018	Mintz et al.
2018/0184988	A1	7/2018	Walker et al.
2018/0214011	A1	8/2018	Graetzel et al.
2018/0217734	A1	8/2018	Koenig et al.
2018/0221038	A1	8/2018	Noonan et al.
2018/0221039	A1	8/2018	Shah
2018/0240237	A1	8/2018	Donhowe et al.
2018/0250083	A1	9/2018	Schuh et al.
2018/0271616	A1	9/2018	Schuh et al.
2018/0279852	A1	10/2018	Rafii-Tari et al.
2018/0280660	A1	10/2018	Landey et al.
2018/0286108	A1	10/2018	Hirakawa
2018/0289243	A1	10/2018	Landey et al.
2018/0289431	A1	10/2018	Draper et al.
2018/0308247	A1	10/2018	Gupta
2018/0325499	A1	11/2018	Landey et al.
2018/0326181	A1	11/2018	Kokish et al.
2018/0333044	A1	11/2018	Jenkins
2018/0360435	A1	12/2018	Romo
2018/0368920	A1	12/2018	Ummalaneni

(56) **References Cited**

U.S. PATENT DOCUMENTS

2019/0000559	A1	1/2019	Berman et al.
2019/0000560	A1	1/2019	Berman et al.
2019/0000566	A1	1/2019	Graetzel et al.
2019/0000576	A1	1/2019	Mintz et al.
2019/0046814	A1	2/2019	Senden et al.
2019/0066314	A1	2/2019	Abhari
2019/0083183	A1	3/2019	Moll et al.
2019/0086349	A1	3/2019	Nelson
2019/0105776	A1	4/2019	Ho et al.
2019/0105785	A1	4/2019	Meyer
2019/0107454	A1	4/2019	Lin
2019/0110839	A1	4/2019	Rafii-Tari et al.
2019/0110843	A1	4/2019	Ummalaneni et al.
2019/0117176	A1	4/2019	Walker et al.
2019/0117203	A1	4/2019	Wong et al.
2019/0151148	A1	4/2019	Alvarez et al.
2019/0125164	A1	5/2019	Roelle et al.
2019/0167361	A1	6/2019	Walker et al.
2019/0167366	A1	6/2019	Ummalaneni
2019/0167367	A1	6/2019	Walker et al.
2019/0175009	A1	6/2019	Mintz
2019/0175062	A1	6/2019	Rafii-Tari et al.
2019/0175287	A1	6/2019	Hill
2019/0175799	A1	6/2019	Hsu
2019/0183585	A1	6/2019	Rafii-Tari et al.
2019/0183587	A1	6/2019	Rafii-Tari et al.
2019/0216548	A1	7/2019	Ummalaneni
2019/0216576	A1	7/2019	Eyre
2019/0223974	A1	7/2019	Romo
2019/0228525	A1	7/2019	Mintz et al.
2019/0246882	A1	8/2019	Graetzel et al.
2019/0262086	A1	8/2019	Connolly et al.
2019/0269468	A1	9/2019	Hsu et al.
2019/0274764	A1	9/2019	Romo
2019/0287673	A1	9/2019	Michihata
2019/0290109	A1	9/2019	Agrawal et al.
2019/0298160	A1	10/2019	Ummalaneni et al.
2019/0298460	A1	10/2019	Al-Jadda
2019/0298465	A1	10/2019	Chin
2019/0328213	A1	10/2019	Landey et al.
2019/0336238	A1	11/2019	Yu
2019/0365209	A1	12/2019	Ye et al.
2019/0365479	A1	12/2019	Rafii-Tari
2019/0365486	A1	12/2019	Srinivasan et al.
2019/0374297	A1	12/2019	Wallace et al.
2019/0375383	A1	12/2019	Alvarez
2019/0380787	A1	12/2019	Ye
2019/0380797	A1	12/2019	Yu
2020/0000530	A1	1/2020	DeFonzo
2020/0000533	A1	1/2020	Schuh
2020/0022767	A1	1/2020	Hill
2020/0039086	A1	2/2020	Meyer
2020/0046434	A1	2/2020	Graetzel
2020/0054405	A1	2/2020	Schuh
2020/0054408	A1	2/2020	Schuh et al.
2020/0060516	A1	2/2020	Baez
2020/0093549	A1	3/2020	Chin
2020/0093554	A1	3/2020	Schuh
2020/0100845	A1	4/2020	Julian
2020/0100853	A1	4/2020	Ho
2020/0100855	A1	4/2020	Leparmentier
2020/0101264	A1	4/2020	Jiang
2020/0107894	A1	4/2020	Wallace
2020/0121502	A1	4/2020	Kintz
2020/0146769	A1	5/2020	Eyre
2020/0155084	A1	5/2020	Walker
2020/0170630	A1	6/2020	Wong
2020/0170720	A1	6/2020	Ummalaneni
2020/0188043	A1	6/2020	Yu
2020/0197112	A1	6/2020	Chin
2020/0206472	A1	7/2020	Ma
2020/0217733	A1	7/2020	Lin
2020/0222134	A1	7/2020	Schuh
2020/0237458	A1	7/2020	DeFonzo
2020/0261172	A1	8/2020	Romo
2020/0268459	A1	8/2020	Noonan et al.
2020/0268460	A1	8/2020	Tse

FOREIGN PATENT DOCUMENTS

CN	102316817		1/2012
CN	102458295		5/2012
CN	102973317		3/2013
CN	103735313		4/2014
CN	105559850		5/2016
CN	105559886		5/2016
CN	105611881		5/2016
CN	106821498		6/2017
CN	104931059		9/2018
EP	3 025 630		6/2016
JP	2015519131	A	7/2015
KR	10-2014-0009359		1/2014
RU	2569699	C2	11/2015
WO	03086190	A1	10/2003
WO	WO 05/087128		9/2005
WO	WO 09/097461		6/2007
WO	2013116140	A1	8/2013
WO	2014058838	A1	4/2014
WO	WO 15/089013		6/2015
WO	WO 17/048194		3/2017
WO	WO 17/066108		4/2017
WO	WO 17/167754		10/2017

OTHER PUBLICATIONS

Haigron et al., 2004, Depth-map-based scene analysis for activew navigation in virtual angioscopy, IEEE Transactions on Medical Imaging, 23(11):1380-1390.

Mayo Clinic, Robotic Surgery, https://www.mayoclinic.org/tests-procedures/robotic-surgery/about/pac-20394974?p=1, downloaded from the internet on Jul. 12, 2018, 2 pp.

Ciuti et al., 2012, Intra-operative monocular 30 reconstruction for image-guided navigation in active locomotion capsule endoscopy. Biomedical Robotics and Biomechatronics (Biorob), 4th IEEE Ras & Embs International Conference on IEEE.

Fallavollita et al., 2010, Acquiring multiview C-arm images to assist cardiac ablation procedures, EURASIP Journal on Image and Video Processing, vol. 2010, Article ID 871408, pp. 1-10.

Kumar et al., 2014, Stereoscopic visualization of laparoscope image using depth information from 3D model, Computer methods and programs in biomedicine 113(3):862-868.

Livatino et al., 2015, Stereoscopic visualization and 3-D technologies in medical endoscopic teleoperation, IEEE.

Luo et al., 2010, Modified hybrid bronchoscope tracking based on sequential monte carlo sampler: Dynamic phantom validation, Asian Conference on Computer Vision. Springer, Berlin, Heidelberg.

Mourgues et al., 2002, Flexible calibration of actuated stereoscopic endoscope for overlay inrobot assisted surgery, International Conference on Medical Image Computing and Computer-Assisted Intervention. Springer, Berlin, Heidelberg.

Nadeem et al., 2016, Depth Reconstruction and Computer-Aided Polyp Detection in Optical Colonoscopy Video Frames, arXiv preprint arXiv:1609.01329.

Point Cloud, Sep. 10, 2010, Wikipedia, 2 pp.

Racadio et al., Dec. 2007, Live 3D guidance in the interventional radiology suite, AJR, 189:W357-W364.

Sato et al., 2016, Techniques of stapler-based navigational thoracoscopic segmentectomy using virtual assisted lung mapping (VAL-MAP), Journal of Thoracic Disease, 8(Suppl 9):S716.

Shen et al., 2015, Robust camera localisation with depth reconstruction for bronchoscopic navigation. International Journal of Computer Assisted Radiology and Surgery, 10(6):801-813.

Solheim et al., May 14, 2009, Navigated resection of giant intracranial meningiomas based on intraoperative 3D ultrasound, Acta Neurochir, 151:1143-1151.

Song et al., 2012, Autonomous and stable tracking of endoscope instrument tools with monocular camera, Advanced Intelligent Mechatronics (AIM), 2012 IEEE-ASME international Conference on. IEEE.

(56) **References Cited**

OTHER PUBLICATIONS

Verdaasdonk et al., Jan. 23, 2012, Effect of microsecond pulse length and tip shape on explosive bubble formation of 2.78 μm Er,Cr:YSGG and 2.94 μm Er:YAG laser. Proceedings of SPIE, vol. 8221, 12.
Yip et al., 2012, Tissue tracking and registration for image-guided surgery, IEEE transactions on medical imaging 31(11):2169-2182.
Zhou et al., 2010, Synthesis of stereoscopic views from monocular endoscopic videos, Computer Vision and Pattern Recognition Workshops (CVPRW), 2010 IEEE Computer Society Conference on IEEE.
Konen et al., 1998, The VN-project: endoscopic image processing for neurosurgery, Computer Aided Surgery, 3:1-6.
Shi et al., Sep. 14-18, 2014, Simultaneous catheter and environment modeling for trans-catheter aortic valve implantation, IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2024-2029.
Vemuri et al., Dec. 2015, Inter-operative biopsy site relocations in endoluminal surgery, IEEE Transactions on Biomedical Engineering, Institute of Electrical and Electronics Engineers, <10.1109/TBME.2015.2503981>. <hal-01230752>.
Al-Ahmad et al., dated 2005, Early experience with a computerized robotically controlled catheter system, Journal of Interventional Cardiac Electrophysiology, 12:199-202.
Gutierrez et al., Mar. 2008, A practical global distortion correction method for an image intensifier based x-ray fluoroscopy system, Med. Phys, 35(3):997-1007.
Hansen Medical, Inc. 2005, System Overview, product brochure, 2 pp., dated as available at http://hansenmedical.com/system.aspx on Jul. 14, 2006 (accessed Jun. 25, 2019 using the internet archive way back machine).
Hansen Medical, Inc. Bibliography, product brochure, 1 p., dated as available at http://hansenmedical.com/bibliography.aspx on Jul. 14, 2006 (accessed Jun. 25, 2019 using the internet archive way back machine).
Hansen Medical, Inc. dated 2007, Introducing the Sensei Robotic Catheter System, product brochure, 10 pp.
Hansen Medical, Inc. dated 2009, Sensei X Robotic Catheter System, product brochure, 5 pp.
Hansen Medical, Inc. Technology Advantages, product brochure, 1 p., dated as available at http://hansenmedical.com/advantages.aspx on Jul. 13, 2006 (accessed Jun. 25, 2019 using the internet archive way back machine).
Marrouche et al., dated May 6, 2005, AB32-1, Preliminary human experience using a novel robotic catheter remote control, Heart Rhythm, 2(5):S63.
Oh et al., dated May 2005, P5-75, Novel robotic catheter remote control system: safety and accuracy in delivering RF Lesions in all 4 cardiac chambers, Heart Rhythm, 2(5):S277-S278.
Reddy et al., May 2005, P1-53. Porcine pulmonary vein ablation using a novel robotic catheter control system and real-time integration of CT imaging with electroanatomical mapping, Hearth Rhythm, 2(5):S121.
Slepian, dated 2010, Robotic Catheter Intervention: the Hansen Medical Sensei Robot Catheter System, PowerPoint presentation, 28 pp.
Kiraly et al., 2002, Three-dimensional Human Airway Segmentation Methods for Clinical Virtual Bronchoscopy, Acad Radiol, 9:1153-1168.
Kiraly et al., Sep. 2004, Three-dimensional path planning for virtual bronchoscopy, IEEE Transactions on Medical Imaging, 23(9):1365-1379.
Solomon et al., Dec. 2000, Three-dimensional CT-Guided Bronchoscopy With a Real-Time Electromagnetic Position Sensor A Comparison of Two Image Registration Methods, Chest, 118(6):1783-1787.

* cited by examiner

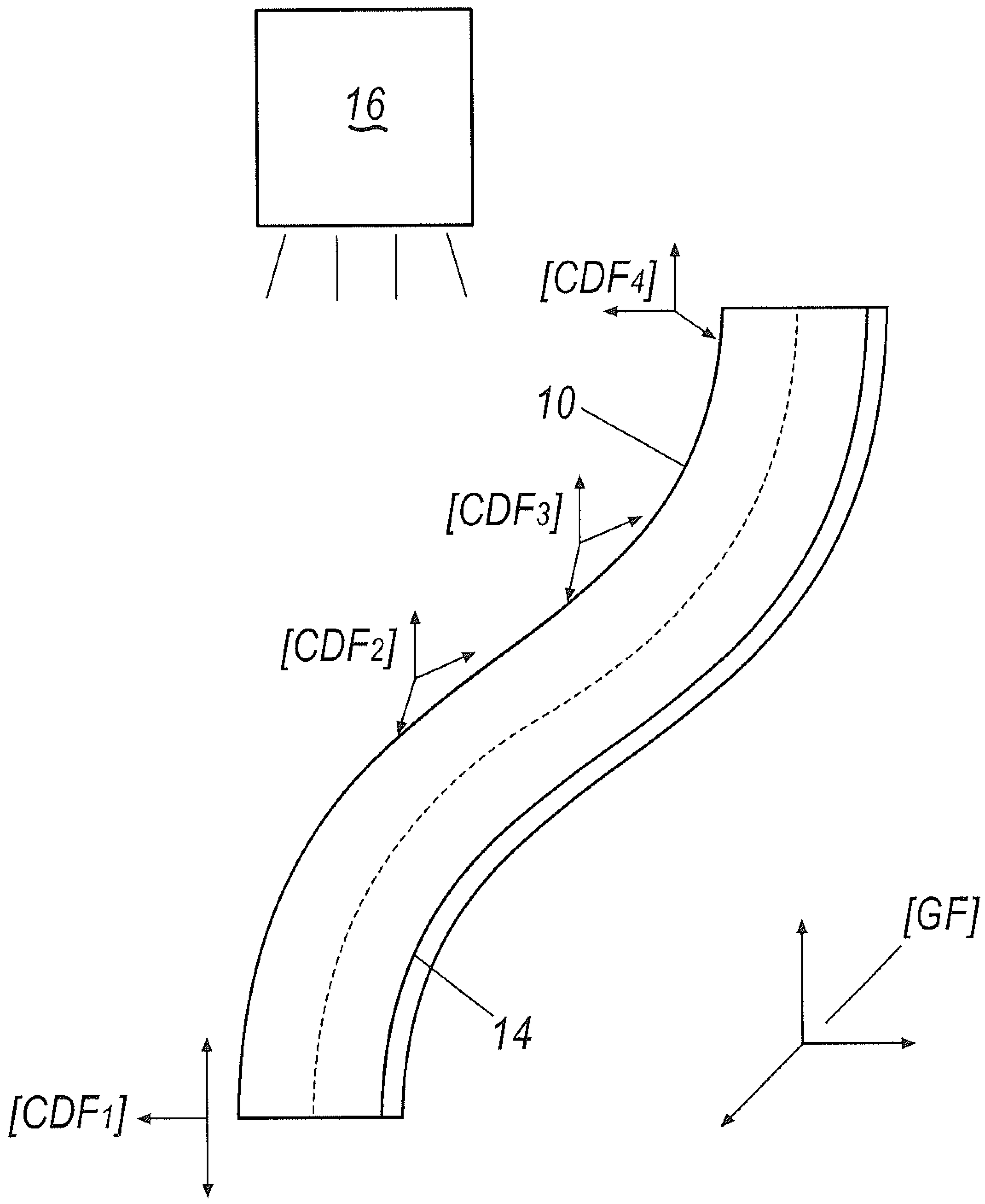

16
[CDF4]
10
[CDF3]
[CDF2]
[GF]
14
[CDF1]

FIG. 1

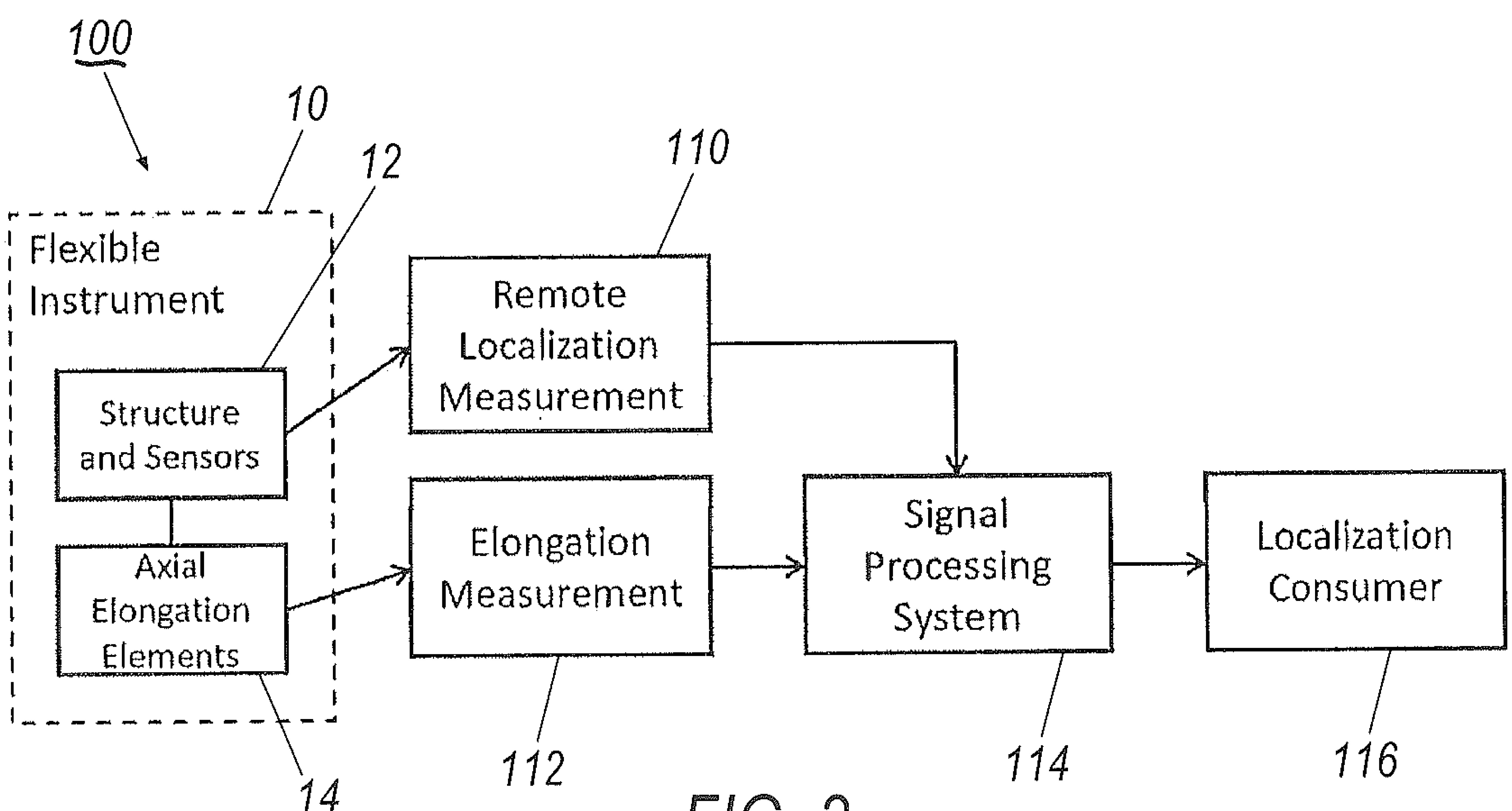
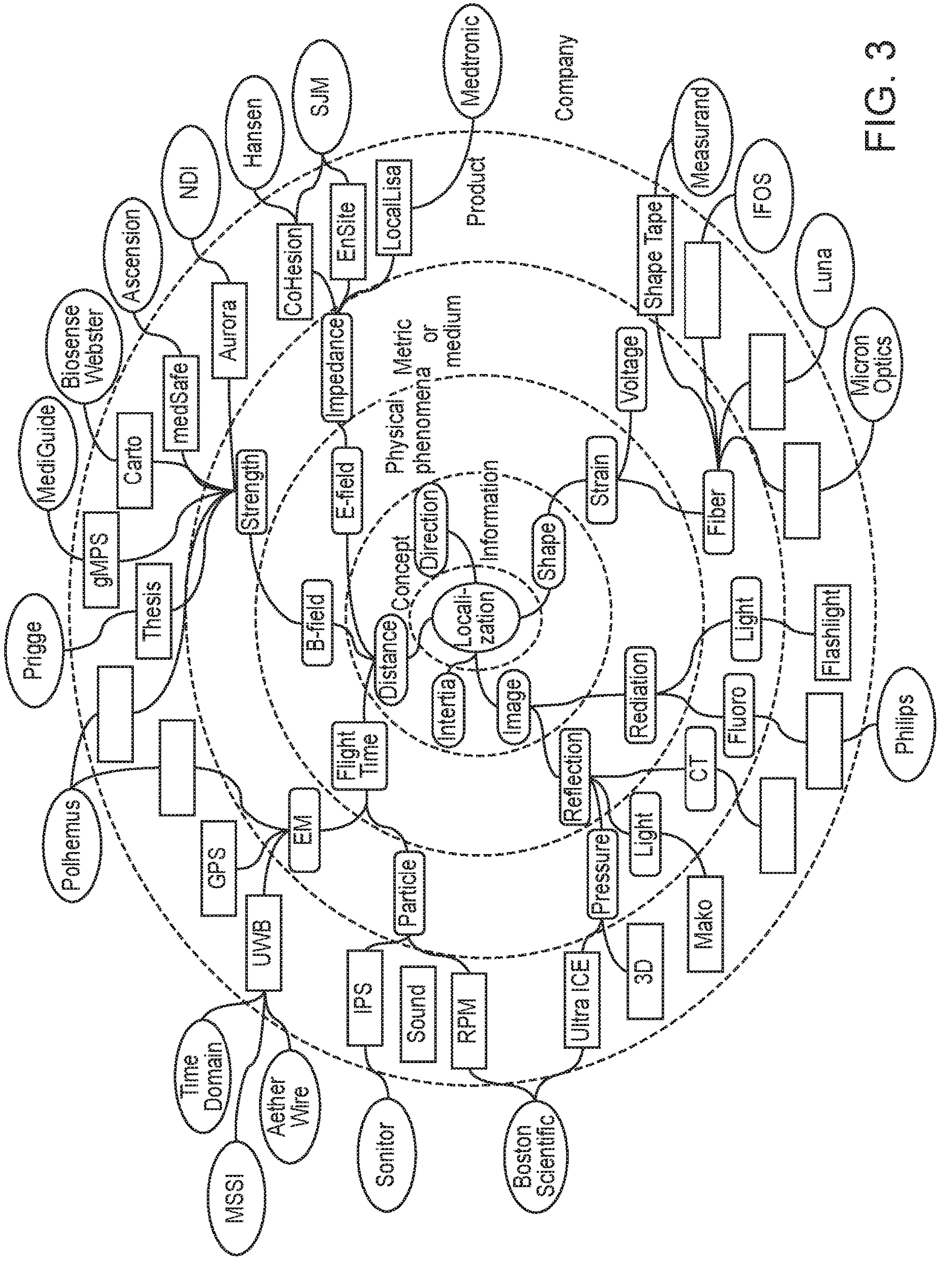

100
10
12
110
Flexible Instrument
Structure and Sensors
Axial Elongation Elements
Remote Localization Measurement
Elongation Measurement
Signal Processing System
Localization Consumer
14
112
114
116

FIG. 2



Company
Product
Physical phenomena
Metric or medium
Concept
Information
Locali-zation
Direction
Distance
Inertia
Image
Shape
Strain
Voltage
Fiber
Shape Tape
Measurand
IFOS
Luna
Micron Optics
Light
Flashlight
Rediation
Fluoro
Philips
CT
Reflection
Light
Mako
Pressure
3D
Ultra ICE
Boston Scientific
Particle
IPS
Sound
RPM
Sonitor
Flight Time
EM
GPS
UWB
Time Domain
Aether Wire
MSSI
Polhemus
B-field
E-field
Impedance
CoHesion
EnSite
LocalLisa
Hansen
SJM
Medtronic
Strength
Aurora
NDI
medSafe
Ascension
Carto
Biosense Webster
gMPS
MediGuide
Thesis
Prigge

FIG. 3

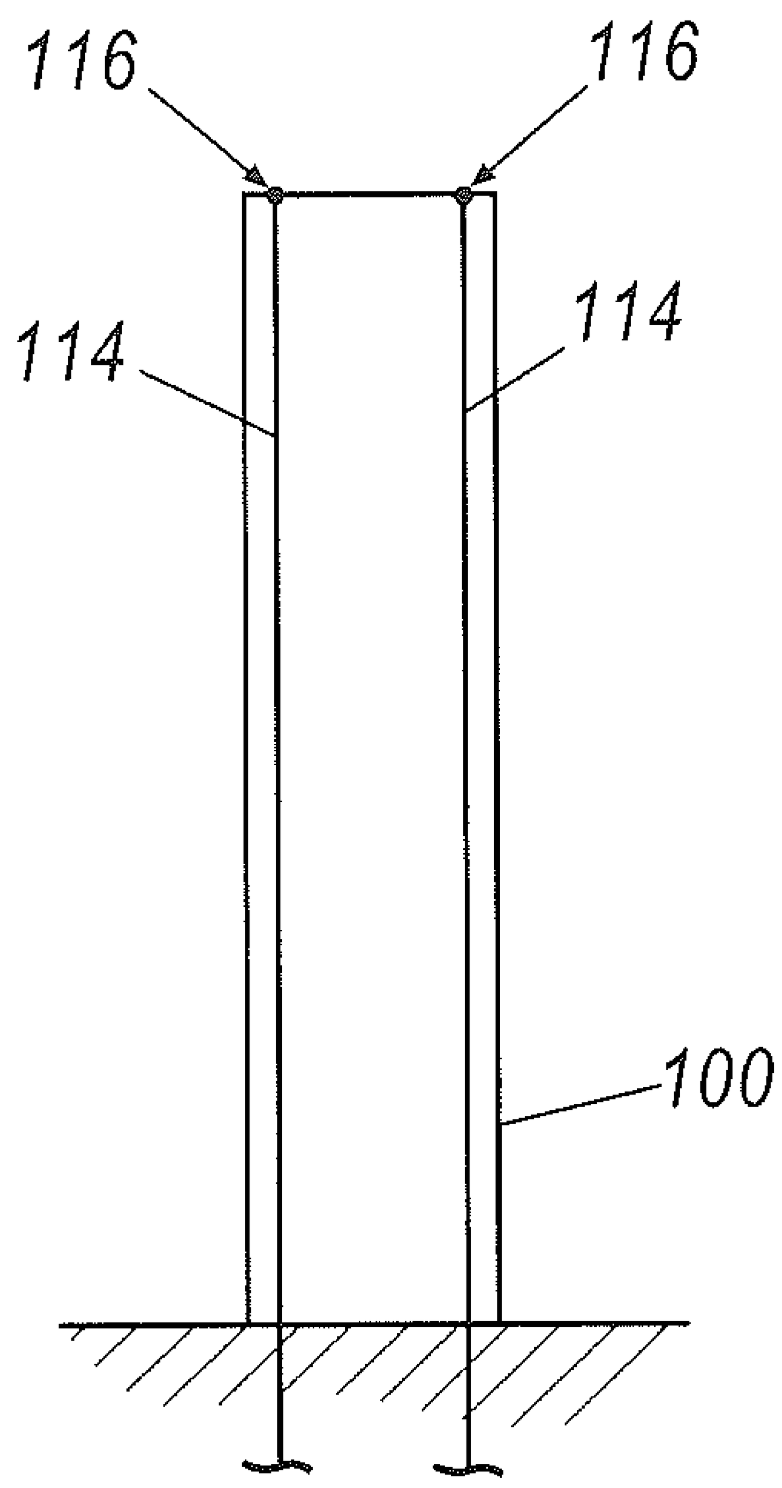


FIG. 4A

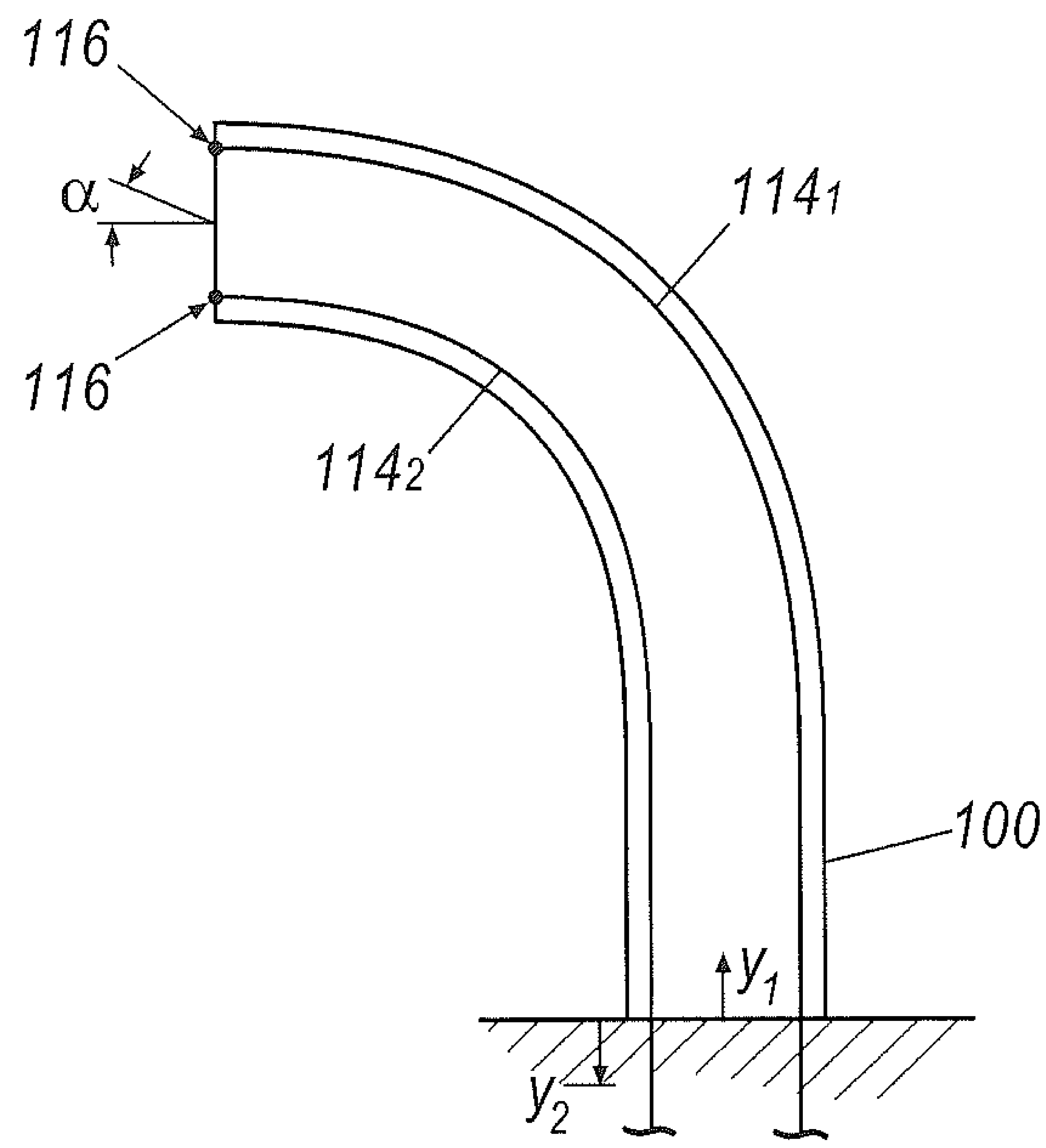


FIG. 4B

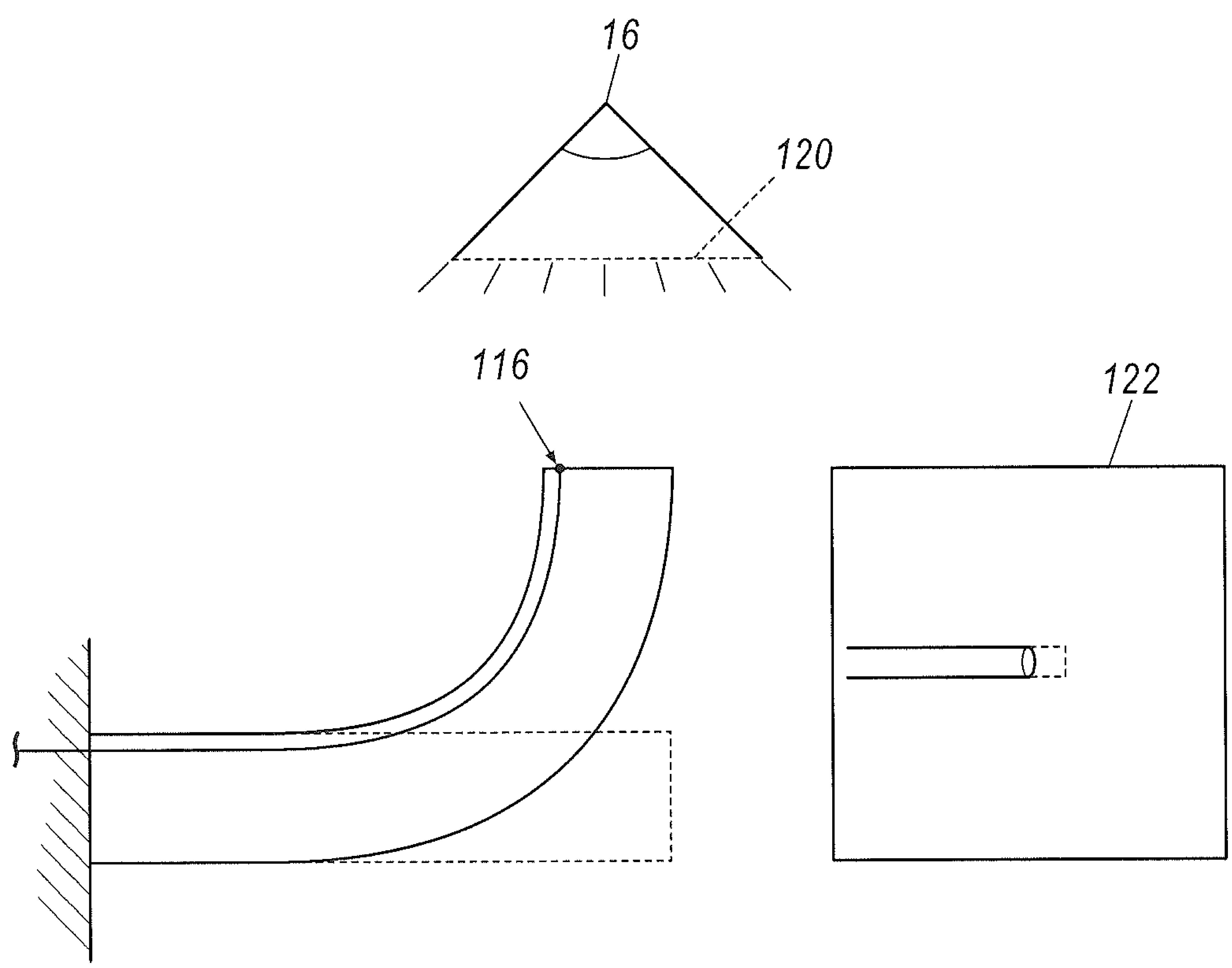


FIG. 5

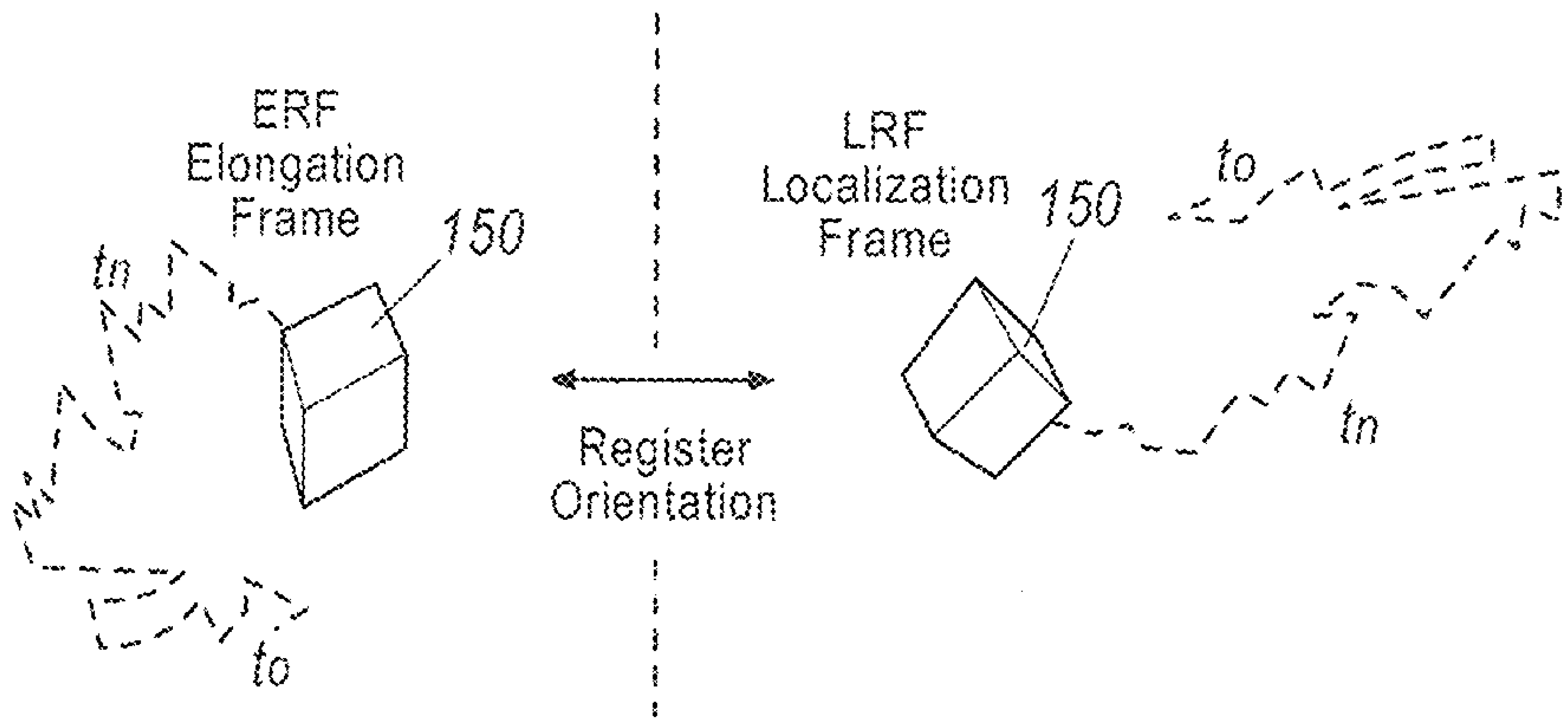

ERF
Elongation
Frame
150
tn
to
Register
Orientation
LRF
Localization
Frame
150
to
tn

FIG. 6

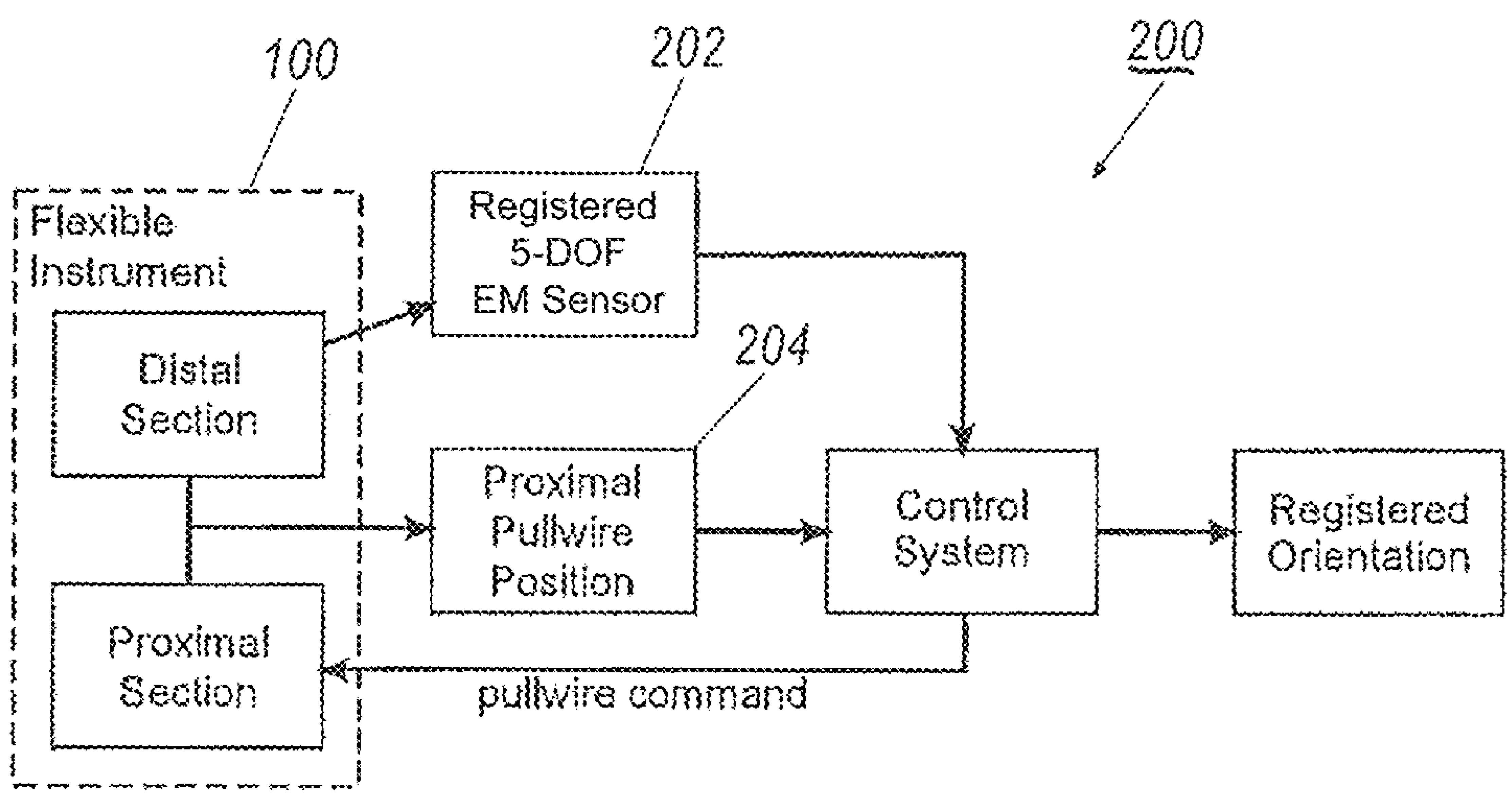

100
202
200
Flexible
Instrument
Distal
Section
Proximal
Section
Registered
5-DOF
EM Sensor
204
Proximal
Pullwire
Position
Control
System
Registered
Orientation
pullwire command

FIG. 7

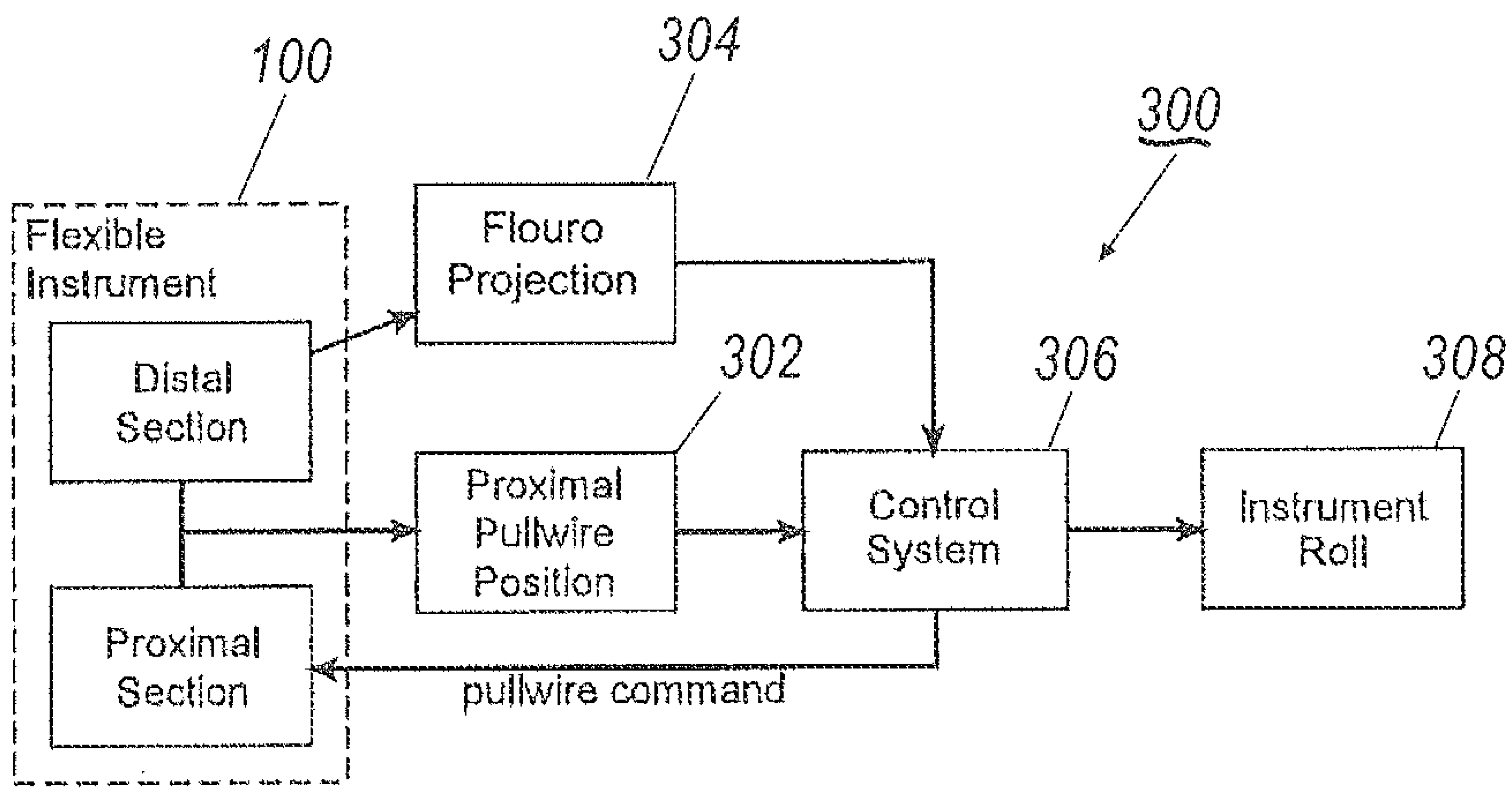

100
304
300
Flexible Instrument
Flouro Projection
Distal Section
302
306
308
Proximal Pullwire Position
Control System
Instrument Roll
Proximal Section
pullwire command

FIG. 8

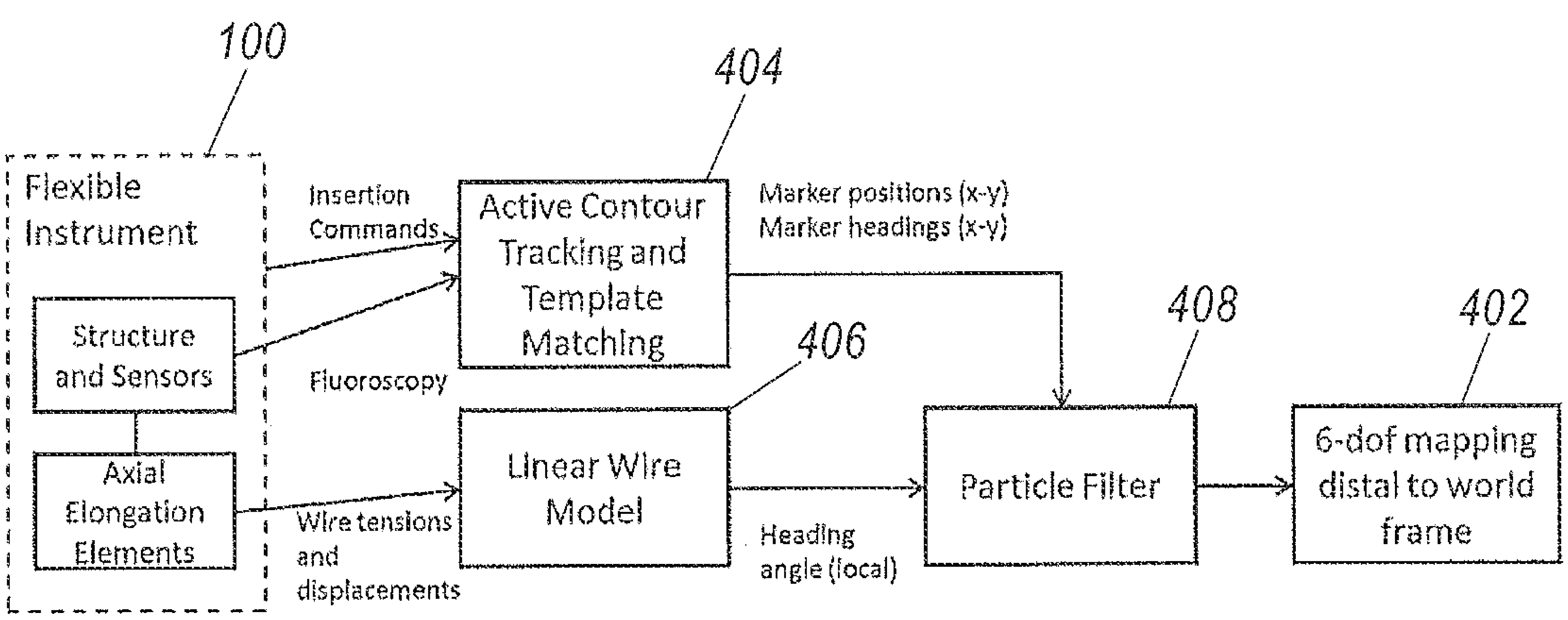

100
404
Flexible Instrument
Insertion Commands
Active Contour Tracking and Template Matching
Marker positions (x-y)
Marker headings (x-y)
408
402
406
Structure and Sensors
Fluoroscopy
Axial Elongation Elements
Wire tensions and displacements
Linear Wire Model
Heading angle (local)
Particle Filter
6-dof mapping distal to world frame

FIG. 9

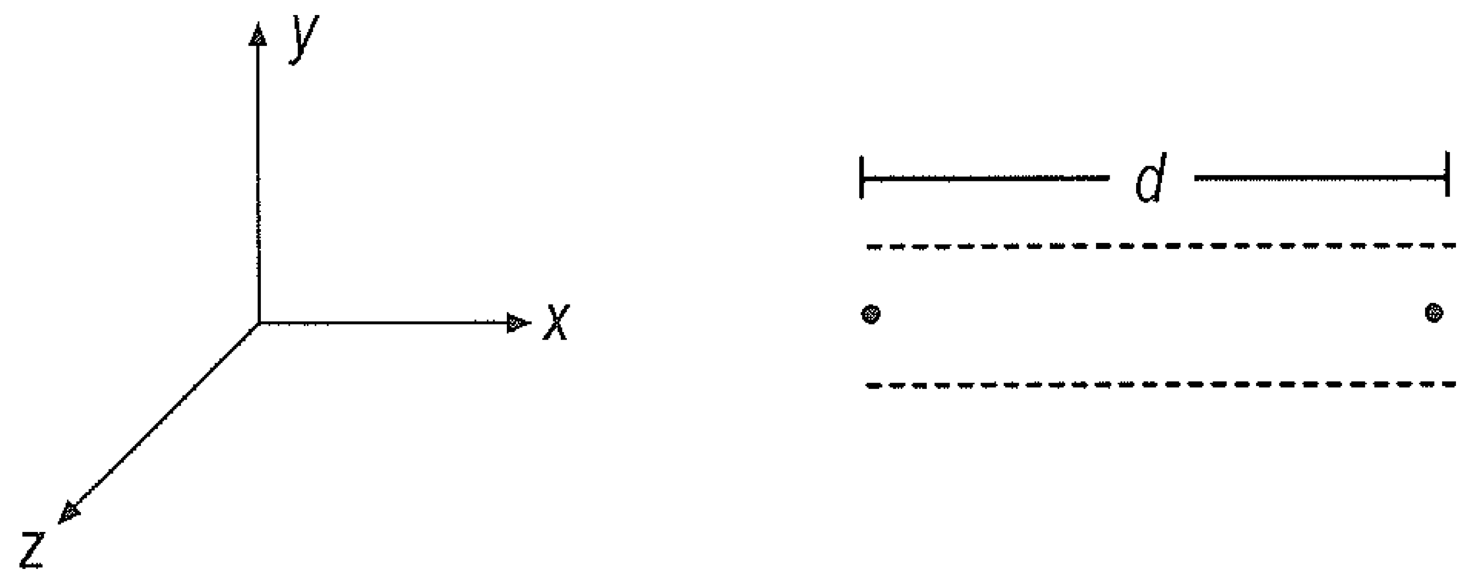


FIG. 10A

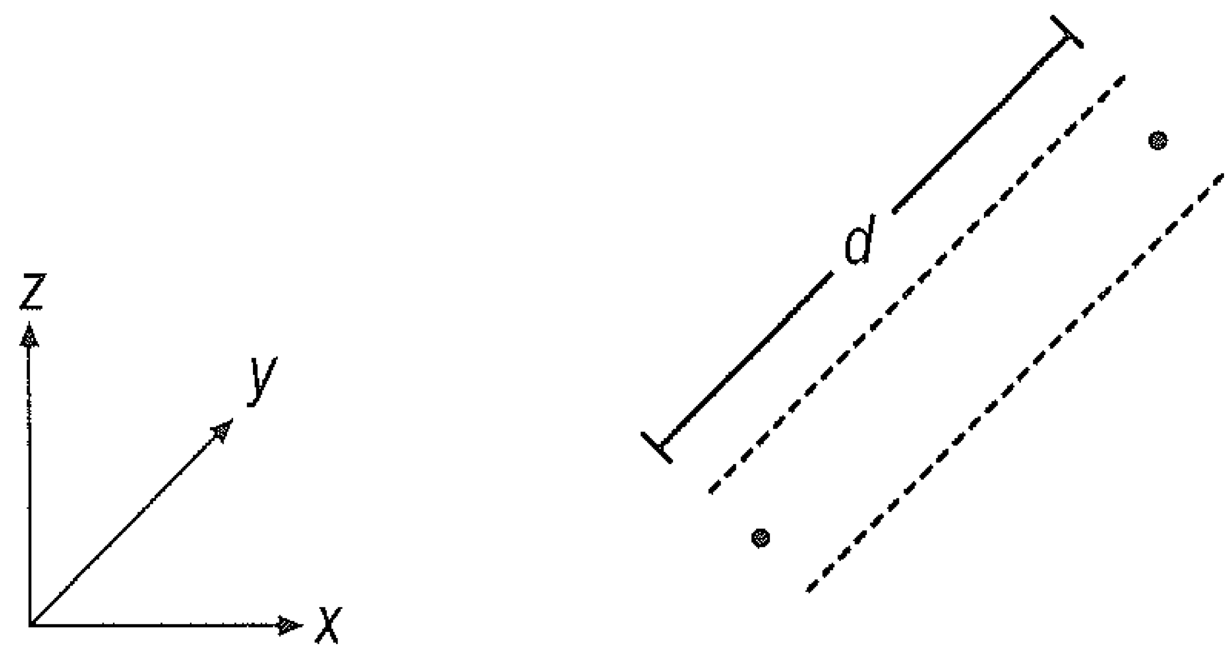


FIG 10B

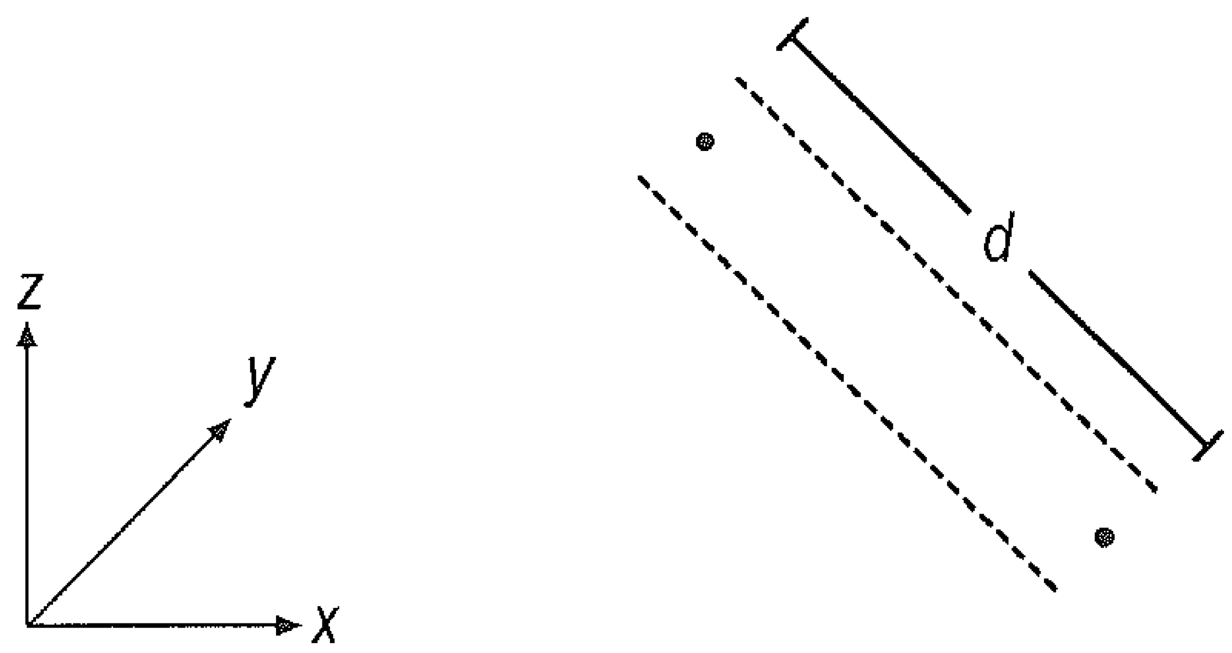


FIG. 10C

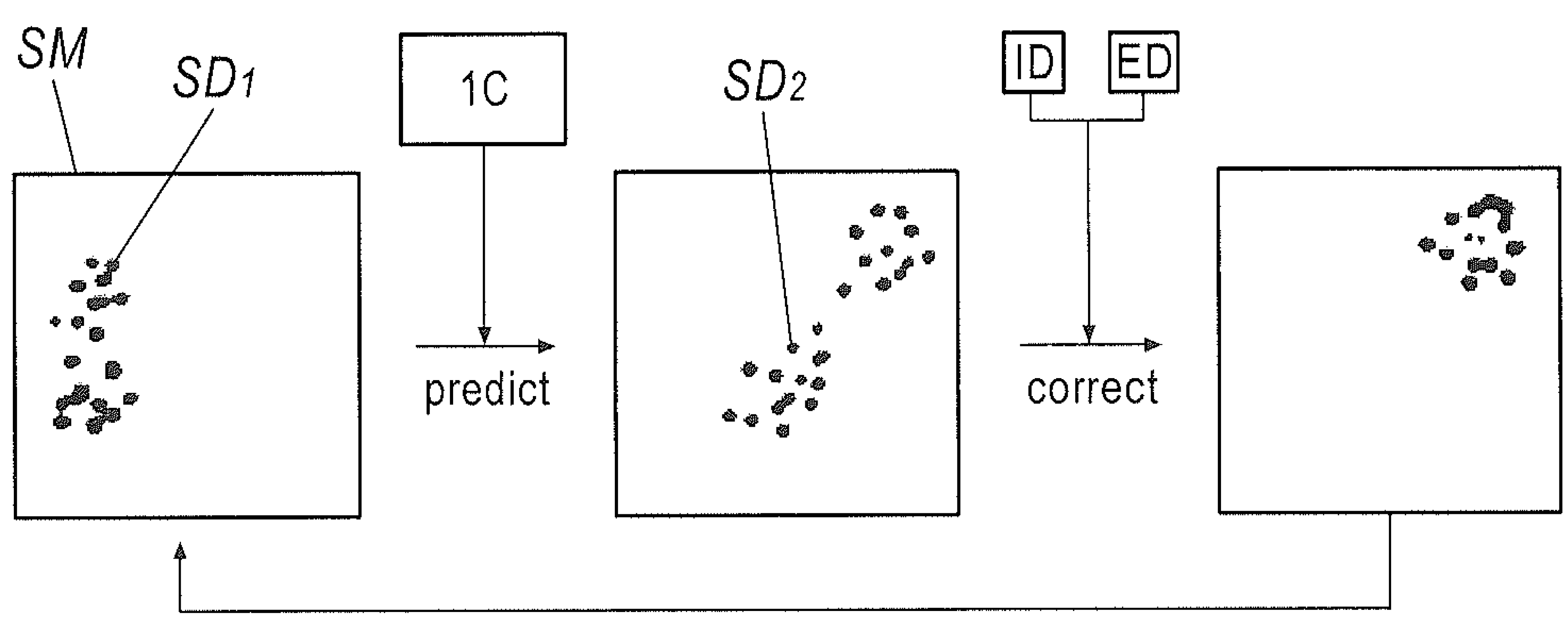


FIG. 11

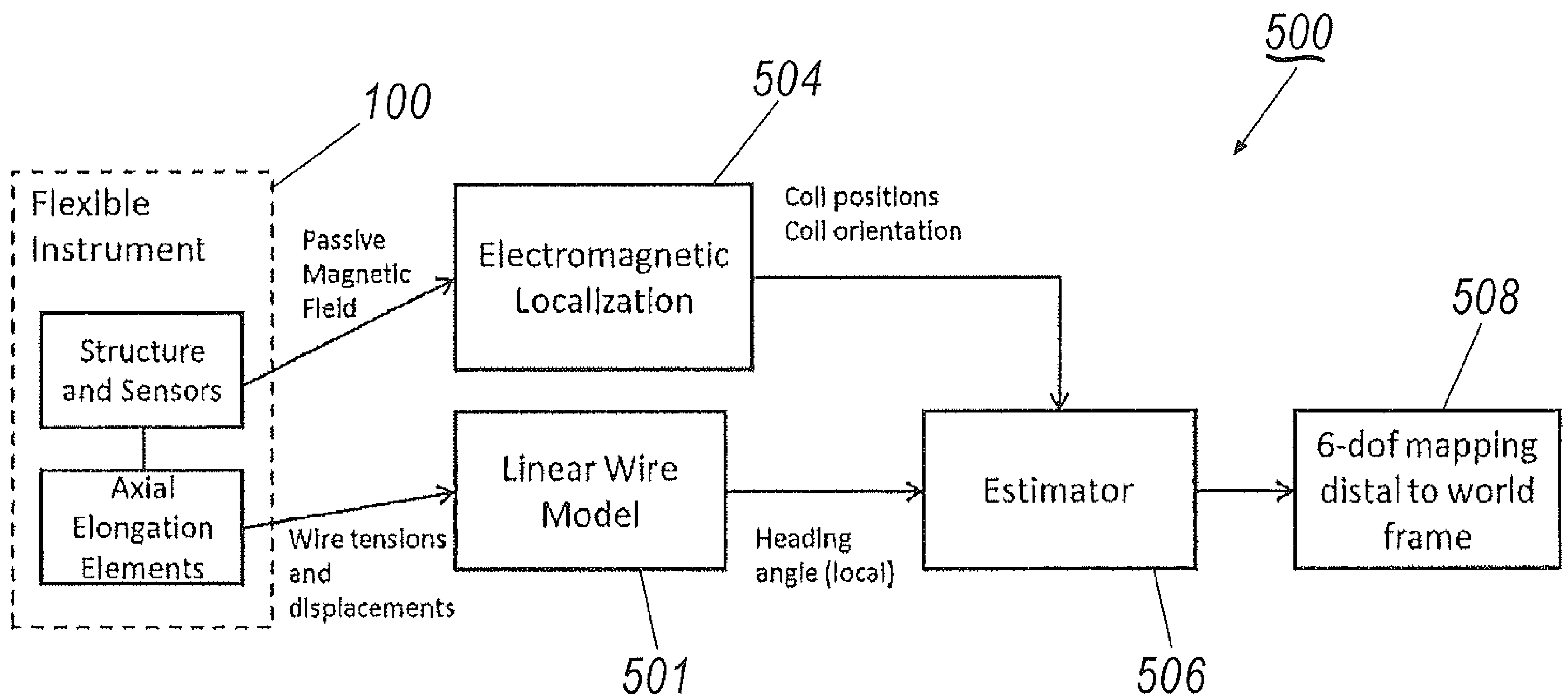

500
100
504
Flexible Instrument
Passive Magnetic Field
Electromagnetic Localization
Coil positions
Coil orientation
508
Structure and Sensors
Axial Elongation Elements
Linear Wire Model
Estimator
6-dof mapping distal to world frame
Wire tensions and displacements
Heading angle (local)
501
506

FIG. 12

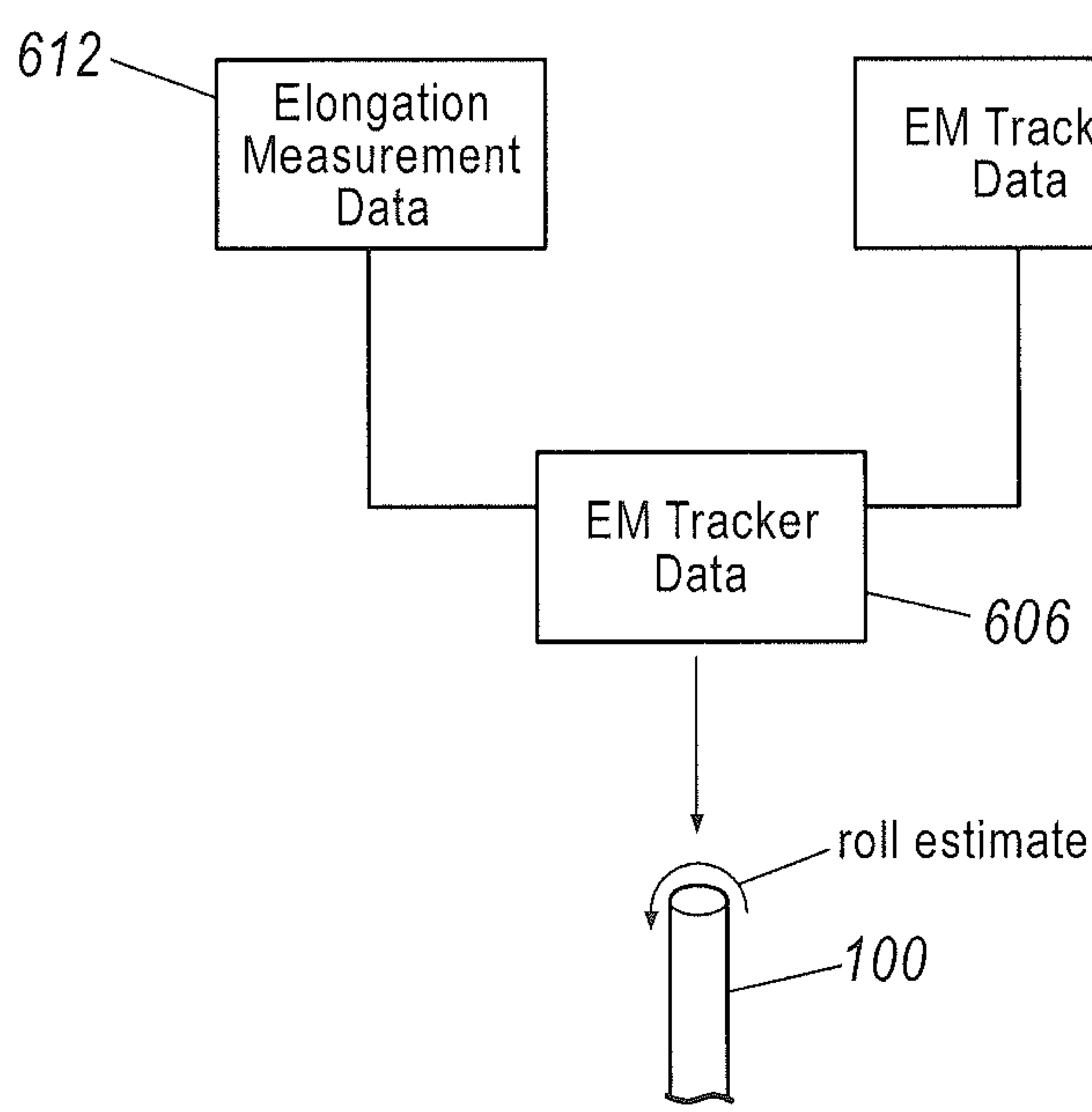

612
Elongation Measurement Data
EM Tracker Data
610
EM Tracker Data
606
roll estimate
100

FIG. 13

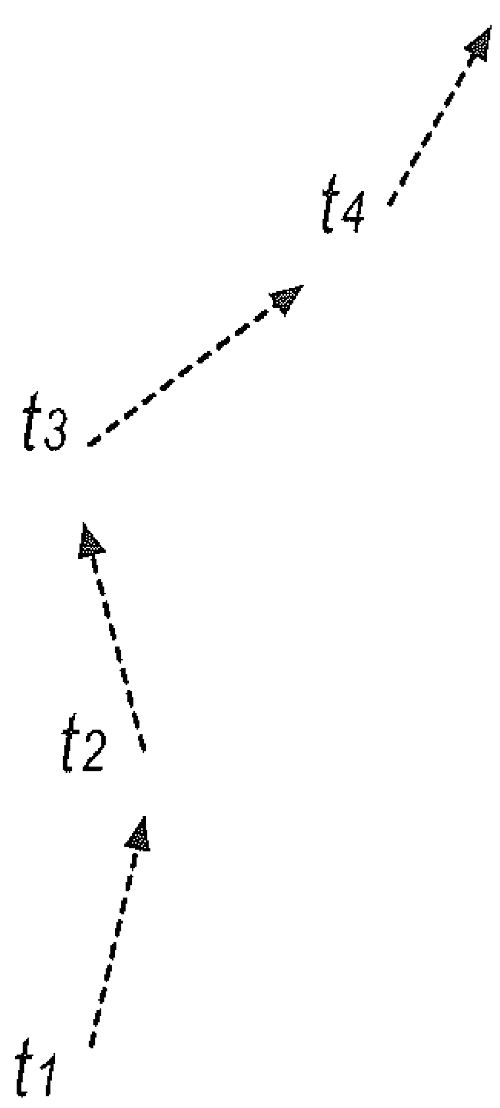


FIG. 14A

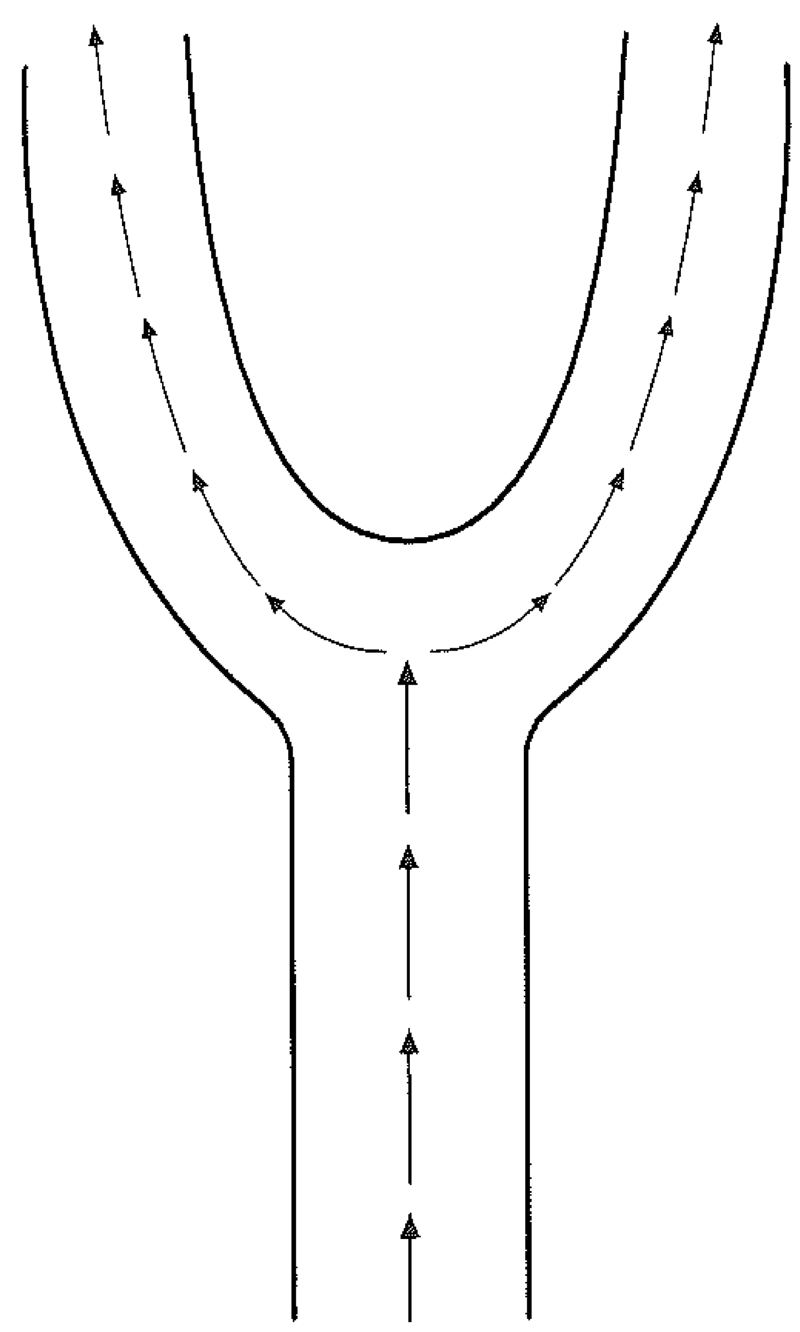


FIG. 14B

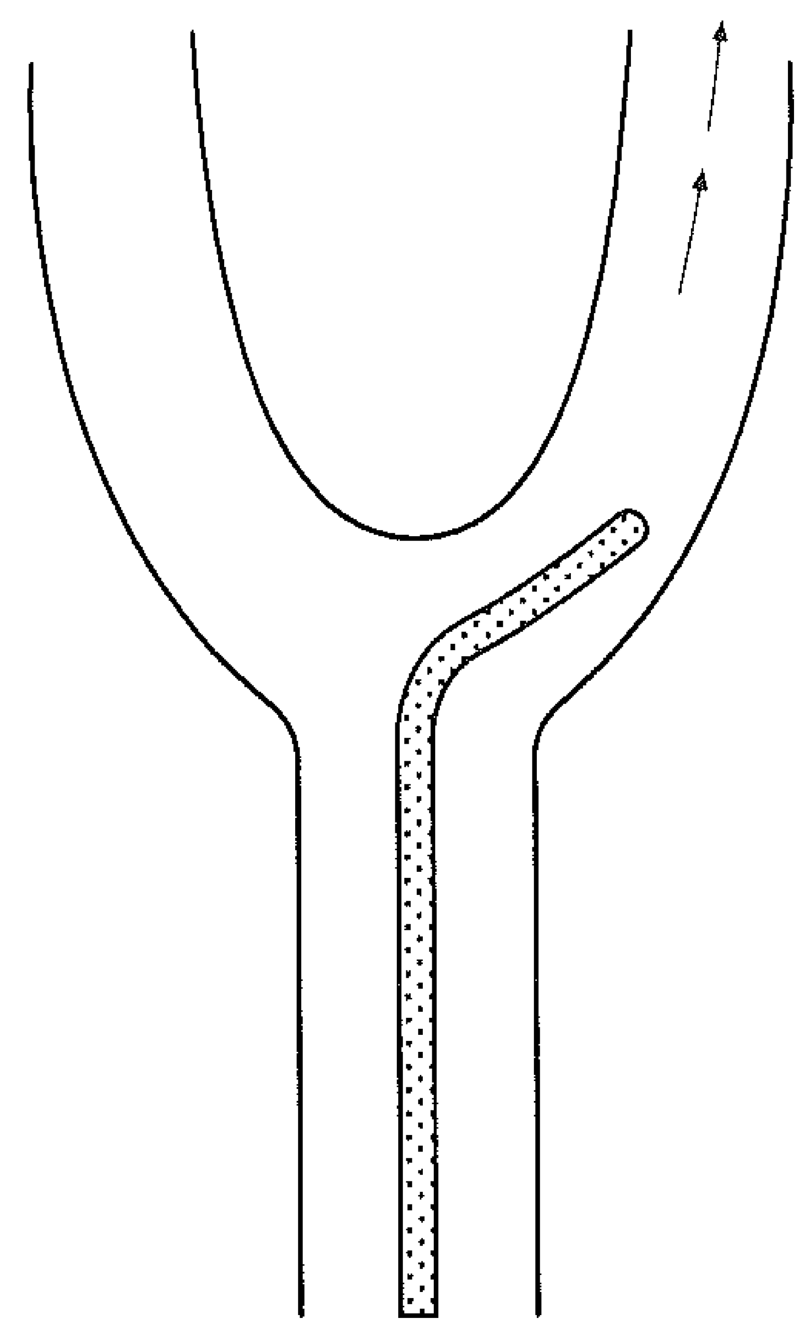


FIG. 14C

FLEXIBLE INSTRUMENT LOCALIZATION FROM BOTH REMOTE AND ELONGATION SENSORS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a Continuation of application Ser No. 13/833,733, filed Mar. 15, 2013, issued as U.S. Pat. No. 9,271,663 on Mar. 1, 2016, and entitled "FLEXIBLE INSTRUMENT LOCALIZATION FROM BOTH REMOTE AND ELONGATION SENSORS." The entirety of which is herein incorporated by reference.

TECHNICAL FIELD

The proposed disclosure utilizes techniques to determine the location, orientation, and shape of a flexible device by utilizing remote localization techniques (such as fluoroscopy, electromagnetic sensors, etc.) with elongation measurements (such as drive wire displacements, tendon tension, etc.) to produce effective localization of the flexible device in a target coordinate frame.

BACKGROUND

Currently known minimally invasive procedures for diagnosis and treatment of medical conditions use shapeable instruments, such as steerable devices, flexible catheters or more rigid arms or shafts, to approach and address various tissue structures within the body. For various reasons, it is highly valuable to be able to determine the 3-dimensional spatial position of portions of such shapeable instruments relative to other structures, such as the operating table, other instruments, or pertinent anatomical tissue structures. Such information can be used for a variety of reasons, including, but not limited to: improve device control; to improve mapping of the region; to adapt control system parameters (whether kinematic and/or solid mechanic parameters); to estimate, plan and/or control reaction forces of the device upon the anatomy; and/or to even monitor the system characteristics for determination of mechanical problems. Alternatively, or in combination, shape information can be useful to simply visualize the tool with respect to the anatomy or other regions whether real or virtual.

However, a primary difficulty in using flexible devices is the inability to determine the location and/or shape of the flexible device within the body. In non-flexible, discrete devices, such detection and monitoring tasks may be accomplished with encoders or other techniques (such as visual tracking of a portion of the device external to the body) that utilized the rigid nature of linkages. Such conventional techniques are not practical with flexible device as such devices contain non-rigid linkages or too many individual linkages to effectively determine location and/or shape of the flexible device.

There remains a need to apply the information gained by the localization techniques to determine the location, orientation and shape of a flexible device and applying this information to produce improved device control or improved modeling when directing a robotic or similar device. There also remains a need to apply such controls to medical procedures and equipment.

SUMMARY

A system and method of tracking a flexible elongate instrument within a patient is disclosed herein. The system is configured to obtain remote localization measurement data of the flexible elongate instrument and obtain elongation measurement data of the flexible elongate instrument. This data is combined and transformed to a coordinate reference frame to produce a localization of the flexible elongate instrument that is more accurate than the remote localization measurements or elongation alone. The combined localization is then provided to a localization consumer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustration of various coordinate frames of an elongation element and a global reference frame;

FIG. **2** is a schematic illustration of a system for localization of a flexible instrument using a remote localization measurement and an elongation measurement;

FIG. **3** is a map of remote localization technologies;

FIG. **4**A is an illustration of a flexible device with actuation elements terminated distally, in an unarticulated configuration;

FIG. **4**B is an illustration of the flexible device of FIG. **4**A in an articulated configuration;

FIG. **5** is a schematic illustration of the flexible device of FIG. **4**B with respect to an imaging plane;

FIG. **6** illustrates how separate orientation frames may be registered to each other by correlating motion of a common object in each;

FIG. **7** is a schematic illustration of a system for localization of a flexible instrument using data from a 5 degrees of freedom electromagnetic sensor with measured pullwire position data;

FIG. **8** is a schematic illustration of a system for localization of a flexible instrument using fluoroscopy imaging data with measured pullwire position data;

FIG. **9** is a schematic illustration of a system for localization of a flexible instrument using active contour tracking and template matching with linear wire model data;

FIG. **10**A-C is a schematic illustration of ambiguities that may occur in and out of an imaging plane;

FIG. **11** is a schematic illustration of an particle filter for filter image and elongation measurements;

FIG. **12** is a schematic illustration of a system for localization of a flexible instrument using electromagnetic localization with linear wire model data;

FIG. **13** is a schematic illustration of a system for using elongation measurement with electromagnetic localization data to determine roll estimation of a flexible instrument;

FIG. **14**A illustrates elongation measurements of a flexible device taken over time;

FIG. **14**B is an illustration of an anatomical map of a vessel; and

FIG. **14**C is an illustration of localization of a device within a map.

DETAILED DESCRIPTION OF THE INVENTION

Overview of Flexible Device Localization

With reference to FIG. **1**, localization of a flexible device **10** will be described. Localization of a flexible device is determining a mapping from one or more device coordinate frames for a flexible device **10** to a global target frame. More specifically, the flexible device **10** of FIG. **1** is defined in terms of localization by one or more Cartesian device reference frames, such as, for example, coordinate frames CDF**1**, CDF**2**, CDF**3**, CDF**4**. These reference frames are typically defined by three-dimensions of position and three dimensions of orientation. Thus, the goal of localization is to determine the relationship, or mapping between the local device reference frames (i.e., CDF**1**, CDF**2**, CDF**3**, CDF**4**) and a fixed, global or target reference frame GF in relation to the task to be performed. The mapping is performed using a combination of one or more remote localization measurements LM (which will be referenced to the global reference frame) and an elongation measurement EM (which will be referenced to the device itself).

An exemplary technique of utilizing a remote localization measurement with elongation measurements are particularly useful when the remote localization measurements are insufficient to fully describe the position, orientation, and shape of the flexible device (i.e., mapping for each device reference frame) or remote localization measurements are not accurate enough as a standalone localization technique.

The basic structure for the proposed localization technique **100** is illustrated in FIG. **2**. The proposed localization technique **100** utilizes both remote localization measurements **110** and elongation measurements **112**. Elements of technique **100** are discussed in further detail below.

The flexible device **10** may be any device that contains continuously articulating joints (including, but not limited to, a manual catheter, robot catheter, etc.). Alternatively, the flexible device **10** may be configured as a device that includes a substantial number of rigid linkages that makes modeling kinematics of the device **10** difficult and unmanageable. The device **10** may include one more sensors **12**. The device **10** may also include one or more elongation elements **14**. Sensors **12** and elongation elements **14** will be described below in further detail.

A remote localization device is any signal from a sensor **12** that is positioned outside of the flexible device **10** that is registered to the global reference frame GRF. An example of a remote localization device is a fluoroscopy system **16**, shown in FIG. **1**. The fluoroscopy view provides the shape and location of flexible device **10**, although certain information, such as depth, cannot be measured. The remote localization device can accurately sense the shape of the flexible device **10**, usually through the use of markers or sensors mounted on the flexible device **10**, as well as sensing the flexible device **10** in relation to a reference frame outside of the flexible device **10**. Various technologies that may be used for remote localization are discussed in further detail below.

As depicted in the schematic of FIG. **1**, an elongation element **14** is an axially disposed element located within the flexible device **10**. Elongation element **14** may take various forms, but its primary purpose is to measure differences in an axial path length APL between a reference path RP within the flexible device **10**. In one exemplary configuration, the reference path RP is a center axis of the flexible device **10** and a secondary path is positioned off the center axis. One exemplary configuration of an elongation element **14** is a tendon that may be used to articulate the flexible device **10**. However, it is understood that any element that allows a differential measurement between two axial paths of the flexible device **10** may be used to calculate an elongation measurement. The primary use of the differential measurement from an elongation element is to determine the approximate shape and heading of the flexible device **10**.

It is also understood that an elongation measurement is not limited to displacement measurements from stretching. Alternatively, elongation measurements such as compression, tension in an element fixed at either the proximal or distal end of the flexible device **10**, or displacement of fluid in a tube may be used. Elongations measurements are discussed in further detail below.

Because the information gleaned from the sensors **12** and the elongation elements **14** are disparate streams of data, a signal processing system **114** that can combine the two data streams into a single localization signal is proposed. There are a variety of methods that may be used with the signal processing system **114**. However, a primary element of the signal processing system **114** is a method of representing the possible shapes of the device in the global reference frame and using sensor information to reduce the number of possibilities. Filters, estimation, and modeling are suitable techniques for accomplishing effective mapping between position and orientation of multiple points on the device and the global reference frame GRF. In addition, commands for a flexible robot may be incorporated into the signal processing system to increase accuracy.

The signal processing system **114** is coupled to a localization consumer **116**. The localization consumer **116** is the eventual user of the relationship between the flexible device **10** and the global reference frame GRF. Non-limiting examples include a robot control system, a sensing system for recording a surgical procedure, or a graphical display utilized by a human operator.

Remote Localization Overview

As discussed above, a number of technologies may be used to determine the shape and position of a flexible device **10** with respect to a fixed reference frame GRF using sensors **12**. In the context of medical devices, including, but not limited to medical catheters, the reference frame may be defined by a part of the patient's anatomy, the table upon which the patient lies, or the world. Complete configuration of a rigid three-dimensional object may be specified by six degrees of freedom. These degrees of freedom are described by three positional coordinates (e.g., the x, y, and z coordinates of a Cartesian frame) and three rotational coordinates (e.g., roll, pitch, and yaw).

Depending on which type, and the number of sensors **12**, a localization system may measure the configuration of a flexible device **10** with respect to all six degrees of freedom, or a subset thereof. For example, a 2 dimensional sensor may determine the position of a given point on the flexible device **10** as projected onto a fixed plane. A 3 dimensional sensor may determine the complete 3D position of a given point on a flexible device **10**, but not the rotation of the flexible device **10**. A 2 degrees of freedom directional sensor may measure the heading direction (pitch and yaw) of the flexible device **10**, but not its roll about that axis. A five degrees of freedom sensor may measure both the position and heading of an object. A five degrees of freedom localization system can constructed from two 3D positional sensors, with the heading direction determined by the vector between them. In a sufficiently constrained anatomy, a 3 degrees of freedom position sensor may be combined with a 3D map (generated from a preoperative imaging scan, such as a CT scan), registered to the same reference frame as the sensor, in order to estimate the heading direction of flexible device **10** (modulo a 180 degree rotation) under the assumption that the flexible device **10** must be in the direction allowed locally by the anatomical map. A six degrees of freedom sensor may full specify the position, roll, pitch, and yaw of the flexible device **10**.

As demonstrated in FIG. **3**, a variety of physical phenomena may form the basis for a localization system. Many systems operate by determining a distance of one or more sensors from reference locations and triangulating a position based on that data. For example, some systems determine the distance by measuring impedance of an electric field. In one known system, electrodes on a flexible catheter and a plurality electrical patches placed on the patient's body are used to compute the 3D position of at least two electrodes, thereby resolving five degrees of freedom. In another known system, six degrees of freedom are resolved by using magnets and a sensor that measures the strength of the magnetic field. In still another known system, time-of-flight waves between emitters and receivers are measured. For example, for GPS, radio waves may be used. In ultra-sound based systems, pressure waves may be used.

An imaging system (such as a fluoroscopy system **16**) may also be used to localize a flexible device **10** with respect to its camera frame when coupled with an algorithm that can detect one or more specified points of the flexible device **10** within the image. Certain imageable materials (such as radio-opaque markers) may be used to enable the specified points to stand out on the image. If only a single point is tracked by the algorithm, a 2D position of the object as projected onto the imaging plane may be determined. If two points are tracked, one rotational degree of freedom may also be computed. More specifically, the heading direction as projected onto the imaging plane may be determined. The distance between the two points, distinct texturing of the markers, and/or simultaneous imaging and tracking in another image plane can be used to determine the heading direction in or out of the original imaging plane. The simultaneously imaging and tracking in different planes may also be used to resolve the third positional coordinate. Further, distinctive texturing of the markers may also be used to estimate the final rotational degree of freedom, i.e., roll.

While remote localization sensors may aide in determining some information about the location of a flexible device **10** disposed within a body, often the sensors are unable to capture important information. For example, as discussed above, a fluoroscopy image is usually a single, planar projection. Thus depth information is not present. As another example, coil electromagnetic sensors disposed within the flexible device may not be able to sense roll about a principal axis. Thus, a supplemental source of information to compliment the information obtainable by remote localization sensors may lead to greater accuracy in localization.

Elongation Measurements Overview

As illustrated in FIG. **2**, information about deformation of a flexible device **10**, which may be obtained from elongation sensors, may be used to supplement information obtained by remote localization sensors. The deformation information may be transmitted for the length of the flexible device **10** by a member that may be configured to elongate or contract based on its relative placement to the centroid of the flexible device **10** as the flexible device **10** articulates.

In a catheter, for example, one exemplary source of elongation information would be actuation elements **14** that move to selectively articulate the catheter. Referring to FIGS. **4**A-**4**B, a catheter **100** includes at least a pair of tendons **114** that each include a first end **116** that is terminated distally. As the first end **116** is displaced proximally, illustrated in FIG. **4**B, a distal motion results. Thus, for the catheter **100** to bend, the material at the circumference of the catheter **100** must either elongate or compress. The motion of the tendon **114** gives an indication of the degree of elongation, and therefore the extent of the articulation. This information can assist in predicting the location and/or orientation of the catheter **100** within the body, especially if the bending motion flexible device **10** is out of a fluoroscopy plane, as illustrated in FIG. **5**. Indeed, as may be seen in FIG. **5**, for a catheter motion out of the fluoroscopy plane **120**, only a small catheter tip motion will be observed on an image panel **122** as the bulk of the motion is toward the fluoroscopy plane **120**.

In the case of a catheter **100** being oriented in a straight line within a patient, the pitch and yaw angles of the catheter **100** can be related linearly to the tendon **114** displacements, as represented by the following formula:

$$\propto = f(y1, y2). \qquad [1]$$

For more complicated anatomy where the catheter **100** will curve and twist, external remote localization may assist with a global reference frame GRF, whereas elongation measurement may be desirable for local differential measurements.

Displacement of a tendon **114** may be indicative of elongation on the circumference of the catheter **100**. However there may be some components that must be compensated for. As a non-limiting example, if the tendon **114** is under load and stretches, an indication of its force may be used to remove its own strain. Similarly, the total force on the catheter **100** may indicate compression of the catheter **100** that must be compensated for since the differential elongation of the catheter **100** from one side to the other side is the quantity of interest. If multiple tendons **114** are used, their respective differential displacement information may be sufficient to indicate orientation.

Although tendons **114** are one example as a source of elongation information, there are other potential sources that are contemplated by the present discussion. One non-limiting example includes an electrical lead that may be routed circumferentially, but configured to float within a lumen. The electrical lead may be used for obtaining elongation information as it displaces.

Instrument channels may also provide a mechanism for measuring elongation if such channels are positioned off center of the flexible device **10**. In one exemplary configuration, the instrument channel is fixed distally. In another exemplary configuration, instrument channel is fixed proximally and measured distally by either internal or external sensing. In yet another exemplary configuration, instrument channel may be fixed at either end, elongation is measured at both the distal and proximal ends.

In yet another exemplary configuration, a pressure filled circumferential lumen may be utilized. More specifically the lumen is filled with either gas or fluid which may be used to generate signals as the pressure and/or displaced volume changes with articulation. Further, the pressure filled lumens may also be used to exert positive pressure or negative pressure to articulate the flexible device **10**.

In a further exemplary configuration, pushrods may be utilized. More specifically, pushrods may be pushed or pulled to articulate the flexible member. Displacement/force may be measured to estimate circumferential elongation on the flexible device.

When using a tension element, such as a cable, use of a Bowden Coil (also known as a coil tube) that can support the tension distally and decouple the flexible shaft motion from tendon actuation may be useful. The Bowden Coil itself could then be measured for device elongation information, as the Bowden Coil must displace back and forth as the device shaft is articulated. However, the Bowden Coil is most likely to be under significant load and therefore compress during articulation. Thus, the load should be estimated and compensated for in calculating the device elongation.

The Bowden Cable may be used in tandem with a tendon **114**. The elongation measurement from the Bowden Coil may give articulation information at a point along the length of flexible where the Bowden Cables are terminated, and the tendons may provide articulation information about the segment distal to the Bowden Coil termination.

In another exemplary arrangement, a fiber optic line may be used to deliver energy or estimate shape/strain of a flexible device **10**. The proximal motion of the fiber optic line, if fixed distally, would indicate circumferential elongation of the flexible device **10**.

Elongation information of interest is at specific known locations about the circumference of the flexible device **10**. However, elongation at multiple points about the circumference of the flexible device **10** provides value since differential elongation provides an indication of device articulation. Thus in one exemplary arrangement, a plurality of elongate elements may be disposed about the circumference to improve knowledge about the elongation of the flexible device **10**. In one exemplary configuration, the plurality of elongate elements may all be terminated at the distal tip of the flexible device **10** to give fine articulation information. In another exemplary arrangement, the plurality of elongate elements may be terminated (or simply measured) at multiple points along the length of the flexible device **10** to give more complete shape information. Once such exemplary configuration is described above; i.e., utilizing the Bowden Coil with tendons, in which two points along the length of the catheter will generate articulation information. A continuous strain measuring instrument could be embedded and fixed in the flexible device that would provide elongation information at multiple points along the length of the flexible device. If a plurality of these strain measurements are routed in parallel on the length of the flexible device **10**, the differential measurements could provide complete articulation information about any point along the length of the flexible device.

Motion Based Orientation Registration

The remote localization measurement and elongation time history data are useful for registering to orientation in a localization frame, such as global reference frame GRF. FIG. **6** illustrates two views of an object **150** in motion in a pair of reference frames, an elongation reference frame ERF and a localization reference frame LRF. Correlating each measured motion in time allows a combination of the signals and improvement of a localization estimate. For example, separate orientation frames may be registered to each other by correlating motion of a common object in each frame. In certain exemplary arrangements that actuate a flexible device, a rich, but low amplitude identification signal may be embedded in an actuation command to aid in the correlation.

If two reference frames are not registered in orientation, objects appearing in each reference frame will be interpreted as rotated differently to an observer of both, such as shown in FIG. **6**. Rotation values for each translational degree of freedom are thus required to register the elongation reference frame ERF and the localization reference frame LRF.

Thus, to register the orientation, the signal processing system **114** illustrated in FIG. **2** translates elongation measurements **112** into an expected motion in the elongation reference frame ERF of those measurements. Next, the signal processing system **114** determines the orientation (rotation angles) which will best match the expected motion to motion that is measured by the remote localization system **110**. This determination may be accomplished by analyzing the time history of measurements (to infer motion), or by keeping an estimate of the state of the system and updating the estimate based on new measurements. In one exemplary configuration, a level of uncertainty of some states may be accounted for by a Kalman filter.

While the above proposed technique does not register position, in some instances orientation is sufficient for a control system to register its commands to an operator selected reference frame. With certain systems, the proposed orientation registration technique may be able to also register positions over time if the two localization data streams include position measurements. Such systems will require correspondingly more data measurements to register the extra degrees of freedom.

Exemplary configurations of the proposed orientation registration technique are described below. In a first exemplary configuration, a 5 degree of freedom measurement is combined with motion of flexible device **100** with four pullwires actuating near a point of measurement with a proximally measured position. In a second exemplary configuration, the same flexible device **100** with the four pullwires is combined with a 2 degree of freedom fluoroscopic measurement of a projected motion. Each will be discussed in turn.

First Exemplary Configuration

Known five degrees of freedom remote localization systems **200** that are marketed for medical use do not measure the roll of a flexible device **100**. However, roll may be estimated by combining a 5 degree of freedom measurement taken from an electromagnetic sensor **202** with measured pullwire positions **204** in the presence of a multi-dimensional motion path, as illustrated in FIG. **7**. The flexible device **100** may be moved with the pullwires to follow a path so as to involve multiple pullwires. In one example, the path is a circle. During this movement, the time history of the pullwire positions and the remote localization measurements may be captured. The localization measurements are recorded as a matrix y. The pullwires positions are translated into the expected motion path, x, with a roll of zero. A roll matrix A, in the registered frame around the y-axis will translate x into the reference frame of y.

$$A(\theta) = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \tag{1}$$

The roll will satisfy the optimization as follows:

$$\underset{\theta}{\text{minimize}} \; \|y - A(\theta)x\|_2^2. \tag{2}$$

In another exemplary configuration, the roll optimization may be formulated as a state-update estimation.

Second Exemplary Configuration

A second exemplary configuration **300** is illustrated schematically in FIG. **8**. In this proposed technique, registration of flexible device **100** is accomplished by using position data **302** from an actuated pullwire device moving in three dimensions with a projected motion measured in two dimensions **304**. All three rotation angles must be estimated to register orientation of the flexible device **100**. A control system **306** combines the position data **302** from the pullwires with the position data **304** from the fluoroscopy system to register **308** an orientation of the device **100**.

As with the first exemplary configuration discussed above, the pullwire motions are translated to expected device motions. The expected device motions in this exemplary configuration is projected onto a fluoroscopy plane **304**. The pullwires further have a very small amount of motion overlaid constantly.

This technique begins by first assuming that the pullwires lie at a cardinal angel positions, λ. λ is represented by the following:

$$\lambda = \left[0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\right] \tag{3}$$

Next, a rotation matrix for motion in the plane **304** is determined:

$$P(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix} \tag{4}$$

In the rotation matrix, ψ represents the yaw in the fluoroscopy reference frame **304**.

The expected motion is calculated as follows:

$$A(\phi, \theta) = \begin{bmatrix} \sin(\lambda - \phi) & 0 \\ \sin\left(\lambda - \phi - \frac{\pi}{2}\right)\sin(\theta) & \cos(\theta) \end{bmatrix} \tag{5}$$

Where ϕ and θ represents roll, both in the fluoroscopy reference frame **304**. The transformation matrix to apply to motion in each tendon and insert axis is as follows:

$$B(\psi, \phi, \theta) = P(\psi)A(\phi, \theta)$$

Where B∈IR2×5

Small motions may be created and measured using the elongation tendons. Such motions should be translated into motion in a Cartesian direction at the distal section, such as, for example:

$$x = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & \\ 0 & 0 & 1 & 1 & 0 & 0 & \\ 0 & 1 & 0 & 0 & 0 & 1 & \ldots \\ 0 & 0 & 0 & 0 & 1 & 0 & \\ 0 & 0 & 1 & 1 & 0 & 1 & \end{bmatrix} \tag{7}$$

Where the columns in the above matrix each represent a time step and each row represents a direction to be projected onto the measurement plane. $x \in \mathrm{IR}^{5\times N}$ for N time samples. Here x(1) is a sideways motion of the tip caused by actuation of a single tendon.

The measurements in the fluoroscopy plane $y \in \mathrm{IR}^{N\times 2}$, represent two-dimensional motion over the same time-steps used for input matrix. However, mechanical systems have bandwidth limitations such that time steps will be much slower than the sampling rate of system electronics −1 to 10 Hz.

Finally, the difference between the time histories of the estimated motion projection and the fluoroscopy measurement should be minimized by properly selecting the rotation angles, as represented by the below formula:

$$\underset{\psi, \phi, \theta}{\text{minimize}} \; \|y - B(\psi, \phi, \theta)x\|_2^2. \tag{8}$$

With constraints on ψ, ϕ, and θ, the minimization performed by the control system **306** will reveal the proper orientation to register the flexible device frame (i.e., through the use of the proximal pullwire position **302**) to the fluoroscopy frame (through the use of the fluoroscopy projection **304**). In another exemplary configuration, the orientation may be formulated as a state-update estimation.

It is understood that the present disclosure is not limited to the first and second exemplary configuration described above. Indeed, other combinations of motion measured via a remote localization system and elongation measurements may be combined with a signal processing system to register orientation in an elongation reference frame to the localization reference frame and improve localization.

Combining Remote Localization and Elongation Measurement

There are a number of different techniques that may be used to combine remote localization data and elongation data to register a tool or surgical device **100** to a target frame. Several exemplary techniques will now be discussed in turn.

Localization with Fluoroscopy and Elongation Measurements

There are a number of imaging techniques that may be used to project a 3D view of a flexible medical device, such as flexible device **100**, to a 2D planar view. One commonly known and used technique is fluoroscopy, although the techniques presented herein may also be used with any camera view, including visible light and unobstructed views. For ease of explanation, the exemplary proposed technique will be described in the context of a fluoroscopy

With reference to FIG. **9**, there are three main elements to a system **400** that augments an imaging technique with elongation measurements to register a flexible device **100** to a target frame **402**. A first element is computer vision techniques that track the flexible device **100** within a fluoroscopy view to produce a computer vision model **404**. While it is understood that there are many ways to track the flexible device **100**, the primary goal is to process an image (and optionally, device commands) and prior information about the flexible device **100** to produce two-dimensional estimations of the position and heading of known positions on the flexible device **100**. A second element of the system **400** is a model of the elongation elements **406**, such as, for example, control wires, that are used to process tension and/or displacement information so as to estimate a heading and position. A third element of the system **400** is a signal processing element **408** that combines information from the computer vision model **404** and the linear wire model **406** to produce six degrees of freedom that maps the end of the flexible device **100** to coordinate frames of a proximal portion of the flexible device **100**, and an imaging frame. Each element of the system **400** will be discussed below in further detail.

Computer Vision Technique

A primary goal of computer vision technique for remote localization measurement is to obtain estimates of distinguishable features on the flexible device **100** with a coordinate frame of an imaging device. In most known surgical suite setups, the imaging device coordinate frame is registered within the global frame GF, so once the flexible device

100 is localized or registered to the imaging device coordinate frame, it may effectively be registered within the global frame GF.

However, the localization from an imaging device is limited to two dimensions, as the images are two dimensional. More specifically, the position of each distinguishable feature of the flexible device **100** is typically represented as two-dimensional and with an unknown depth. Moreover, orientation from the imaging system may only provide a single degree of freedom—i.e., orientation angel within the plane. Thus, localization from an image gives no indication of the orientation in and out of the plan. Nor is roll around an axis of the flexible device **100** represented. Orientation and roll information can provide valuable information to effect proper localization and registration of a flexible medical device **100** within a target frame.

Tracking multiple features on a flexible device can improve depth and orientation estimates if the distances between each of the features are known. In typical 3D object tracking with computer vision techniques, all six degrees of freedom may be determined using the multiple features, as well as knowledge about occlusions. Thus, for flexible devices **100**, it is possible to estimate the displacement of two reference points in or out of the imaging plane, but not possible to determine if the reference points are positioned in or out of the plane because of the inability to visualize depth.

More specifically, referring to FIG. **10**A, a projection to the x-y image plane is shown. However, the actual depth of the reference points along the z-axis is not possible to determine, even if the distance in the projected plane, d', and the actual distance between the features, d, is known. For example, because the reference point on the right side of the image could be lower or higher than the reference point on the left side of the image, as demonstrated in FIGS. **10**B-**10**C.

There are many methods that may be utilized to track the flexible devices **100** in an image. Exemplary methods include placing specific markers or features, based on color, shape, location, or a combination of thereof, on the flexible device **100** and designing computer vision methods to track those markers and/or features. Other techniques require segmentation of the flexible device **100** from the background using shape, color, density, or motion information and then locating features within the flexible device **100** by exploiting the segmentation.

Another exemplary method is active contour tracking, which is augmented with template matching tuned to the flexible device. Many flexible devices **100** show up in fluoroscopy images as a single solid or textured compound curve. Thus, in such cases it may be useful to track the flexible device **100** shape with an active contour and then locate the specific features on the flexible device **100** with template matching techniques. An active contour is a method of maintaining a set of points on a curve by minimizing an energy function. Terms of the energy function maintain spacing between the points, minimize curvature (since flexible devices **100** resist sharp bends), and proximity to the curve in the image. The end result is a sequence of points that tracks the flexible device **100** and grows or shrinks as the projection of the flexible device **100** grows and shrinks. An active contour can be designed to track edges in the image (using an energy term that is minimized when on an edge) or, in the case of flexible devices **100**, two edges with a darker area inside them. Active contour tracking is described in co-pending U.S. patent application Ser. No. 13/832,586, issued as U.S. Pat. No. 9,629,595 on Apr. 25, 2017, the contents of which are incorporated by reference in its entirety.

An active contour allows tracking of specific flexible device features **100**, such as control rings, markers, or other distinctive features that show up in images, by reducing the search space for image template matching techniques, for example by defining a "local area". Techniques such as correlation coefficients may be used to match specific image features by generating a template image based on heading and construction of the flexible device **100** in the local area of the active contour and finding the position where it best matches the image. This technique results in robust tracking of the shape of the flexible device **100** with a reduced search space for tracking specific features.

Active contour guided template matching is effective in that the active contour provides a good estimate of heading in two dimensions while the template matching provides a good estimate of feature position within two dimensions. Thus the overall system is much more robust to disturbances and can recover lost features faster. Initialization of the tracker can use a human interface or image search for specific features to seed the tracker.

Linear Model of Heading with Angle and Tension

The three to four degrees of freedom information that are acquired from imaging (x and y position, orientation angle around the z axis, and a partial, or ambiguous, position and orientation in z axis), when augmented with elongation measurements, provide full localization. One way of processing elongation measurements from a flexible device **100** is to fit a linear model to the relationship between the displacement and force on the elongation measurements and the orientation of a sensor.

A simple linear model of a planar, two-pull wire flexible device is:

$$\theta=a_0x_0+a_1\tau_0+a_2x_1+a_3\tau_1+a_4 \tag{9}$$

where a_i represents the constants to the linear equations, x_k represents wire displacements, T_k represents wire tensions, and θ represents estimated orientation of the flexible device **100**. a_i can be determined experimentally using a least-squares fit.

The model may be improved if it is known that pairs of pull-wires are antagonistic, or located on opposite sides of the flexible device **100**. In that case, the coefficients of the antagonistic displacements or tensions should be equal and opposite. Equation 9 may be simplified using this information to:

$$\theta=a_0(x_0-x_1)+a_1(\tau_0-\tau_1)+a_2 \tag{10}$$

The primary assumption in Equation 10 is that bending will be entirely kinematic—there will be no torsion around the axis of the flexible device **100**. In this way, it is possible to represent angle as a two-dimensional vector in the plane perpendicular to the flexible device **100** at the base of an articulating section. A pseudo-angle vector, $\vec{\theta}=[\theta_x,\theta_y]$ where the magnitude of $\vec{\theta}$ corresponds to the amount of rotation around the vector defined by unit($\vec{\theta}$). In this representation, it is possible to represent θ_x and θ_y into two equations:

$$\theta_x=a_0(x_0-x_2)+a_1(x_1-x_3)\pm a_2(\tau_0-\tau_2)+a_3(\tau_1-\tau_3)+a_4 \tag{11}$$

$$\theta_y=b_0(x_0-x_2)+b_1(x_1-x_3)+b_2(\tau_0-\tau_2)+b_3(\tau_1-\tau_3)+b_4 \tag{12}$$

Note that each of θ_x and θ_y is expressed as a function of all pull-wire measurements because of the inability to decouple angle directions from the pull wire directions.

The linear model works relatively well, provided that the underlying system is linear. Thus for systems incorporating metal pull-wires and limited friction, the linear model may be applicable. In systems with non-linear pull-wires or complicated friction characteristics (such as coil tubes) a non-linear model may be utilized. However, elongation elements cannot capture the roll angle from torsion. If there is limited torsion however, a linear model is effective for computing the orientation of the distal tip of a flexible device **100** in relation to the proximal end.

Filtering Image Information and Elongation Measurements

While image processing techniques can yield two dimensional position and orientation in a plane (plus some depth information) and a linear model of the flexible device **100** may estimate heading, the combination of the data yielded from the two techniques can produce a much stronger localization estimate. Indeed, the goal of localization estimation is to represent possible configurations of the flexible device **100** given the inputs of imaging data and elongation data and then correlate the two inputs to reduce the number of possibilities. While the elongation measurements map from a proximal device frame to a distal robot frame and the image processing maps from a global (image) frame GF to a distal robot frame, there is enough common information to provide a final mapping from the global frame to the distal device frame, thereby yielding an information filter using the image as one input and the elongation measurements as the second input.

Filtering techniques needed in this case require the ability to represent multi-modal hypotheses. An illustration for using multi-modal hypotheses is provided in FIG. **10**. Because it is ambiguous whether the flexible device **100** is projected in or out of a given plane, two or more separated hypotheses are needed until more information is known. There are many ways of managing a filter with multiple hypotheses, including, but not limited to, the use of multiple Kalman filters, particle filters, and combinations of Gaussians.

In one exemplary configuration, particle filters are used. Particle filters maintain a sampling of a hypothesis space using particles, or discrete estimates. This sampling of a hypothesis space is updated using probability-based coefficients based on expected changes in state and future measurements. The result is a sequence of prediction-correction steps that causes the distribution to converge to the most likely hypothesis or hypotheses. Thus particle filters are well suited to the problem of combining image localization information with elongation measurements. The basic steps of a particle filter technique is represented in FIG. **11**.

More specifically, while a single set of static measurements SM (images and elongation displacements and tensions) can provide valuable information, additional information may be gleaned when the system moves. For example, referring to FIG. **11**, initial measurements of a flexible catheter **100** may be represented by an initial sample distribution SD_1. An input command IC may be directed to move the flexible catheter **100**. Based on the initial data from the sample distribution SD_1, an updated sample distribution SD_2 is generated to predict the movement of the catheter. Next, image data ID and elongation data ED collected may be combined together. The image data ID and elongation data ED may then be used to correct or update the sample distribution SD_3 to provide a more accurate representation of the flexible device **100**. The updated sample distribution SD_3 may then be used as the initial data to repeat the process.

As a further example, if an initial roll orientation of the pull wires is known in relation to the flexible device **100** tip it is possible to recover all six degrees of freedom for localization, but if this roll is unknown or difficult to determine, only five degrees of freedom may be recovered. In contrast, if the system moves, the uncertainty about motion may be compensated in a particle filter by spreading particles in the different possible roll directions. The next set of measurements will then reduce the possibilities related to the roll degree of freedom. This is technique is similar to what is described above in connection with FIG. **8**.

Bowden Coil Supported Tendons

Using fluoroscopy with any number of computer vision algorithms such as those described above, a planar position and heading of a flexible device **100** may be estimated. If the flexible device **100** is a catheter that has one or more articulating segments that are steered by tendons supported by Bowden Coils, information from these mechanical elements may also be used to improve a location estimation by convex optimization.

More specifically, in a vascular procedure there is a proximal portion of the vasculature where a catheter **100** may be inserted without articulation moving toward an anatomical location of interest. During this insertion, a robot can be used to position the tendons so that all tension is removed from the catheter to maintain maximum flexibility during this "passive" insertion. Once the anatomical location of interest has been reached, such as a calcified bifurcation for example, it may be necessary to begin controlled articulation of the catheter **100** to select a branch into which the catheter **100** may be directed. During controlled articulation, it can be helpful to know the location/orientation of the catheter **100** in the anatomy. This may be accomplished using the framework of FIG. **2** whereby the Remote Localization Measurement **110** is obtained from fluoroscopy processed with computer vision algorithms, and the "Elongation Measurement" **112** is obtained from tendon displacements and force.

Once passive insertion is completed, the (while at zero force) can be recorded as a starting tendon position for zero articulation. This will baseline for future tendon motions that articulate the catheter. The fluoroscopic image can, at that point, be processed to obtain a planar position and angle of the flexible device **100**. The localization "signal processing" algorithm may be seeded by assuming that the articulating segment of the catheter **100** lies in the image plane and has zero roll. Therefore, at this first instant, a complete estimate for the orientation of the catheter tip, which would be in the plane of articulation with zero roll, may be determined. This technique assumes that the orientation of the distal termination of the Bowden Coils is coincident with catheter tip to begin.

The next step in the procedure is to apply controlled articulation to access the vessel of interest. At this point, force is applied to the tendons. The pitch, yaw, and roll of the distal tip relative to the reference frame of the distal termination of the Bowden Coils may be estimated based on the tendon displacements and forces using a method, such as, for example, a linear model discussed above. If the initial starting point for the Bowden and tendon termination frames were incorrect, then the fluoroscopy measurements will not coincide with the prediction from the elongation measurements, generating an error signal. This error signal can be used in a convex optimization routine that will generate a new estimate for the Bowden frame that minimizes the error between the fluoroscopy measurement and distal tip estimate from the elongation information. As the catheter **100** is exercised about its workspace, the estimate for Bowden frame should converge so that the out of plane information may be presented to the "localization customer" **116**.

Localization with Electromagnetic Sensors and Elongation Measurements

With reference to FIG. **12**, another proposed system **500** is illustrated that utilizes electromagnetic tracking as a remote localization measurement **504**. The electromagnetic tracking is augmented with elongation measurements **501** by an estimator **506** to register a flexible device **100** to a target frame **508**. In one exemplary configuration, **6** degrees of freedom of the flexible device **100** may be mapped to the global frame **508**.

Electromagnetic (EM) trackers can produce up to six degrees of freedom of localization by embedding coils in the flexible device **100** and measuring induced currents from magnetic fields generated by transmitters. While it is possible for an EM tracker to provide all localization of a flexible device **100**, in some situations it may be desirable to augment electromagnetic tracking with elongation measurements, as illustrated in FIG. **12**.

Electromagnetic trackers are based on induced currents from a changing magnetic field. A current is induced in a receiver coil based on the change in magnetic flux through the coil. Typically, a transmitter turns on and off coils to produce magnetic fields with a known intensity and speed. Then, with knowledge of the size and orientation of the coil in relation to the flexible device **100**, it is possible to estimate the location and/or orientation of the coil. For accuracy and more degrees of freedom, most EM systems use multiple transmitter coils and one or more receiver coils.

A single receiver coil coupled with a multi-coil transmitter can estimate five degrees of freedom—all localization except roll around the axis of the coil. Two or more receiver coils can estimate all six degrees of freedom if the coils are non-parallel, but often the accuracy of such systems is limited due to the size of the device **100**. For instance, a typical flexible device requires very small coils if the device contains a center lumen—and the accuracy of the EM tracker is related to the amount of area enclosed within the coil. The result is that small coils are limited in range from the transmitter and other equipment or ferromagnetic materials in the area can cause warping of the magnetic field and the localization measurements.

Single-Coil Roll Estimation

In the case where only a single coil is incorporated in the device (or multiple coils that are non-collocated and parallel) the EM tracking system will not be able to localize roll. In these situations, the elongation measurements would be useful to determine the roll. It is important to note that the roll of the flexible device cannot be recovered without motion in the flexible device **100** because only the correlation of EM tracker motion and elongation measurement motion allows recovery of roll.

Since the two sensing modalities, namely electromagnetic localization **504** and linear wire modeling **502**, must be correlated with respect to motion, algorithms are needed that can maintain hypotheses of the current roll and update that distribution of hypotheses with each new piece of sensory information. Many types of filters or estimators **506** could be used to maintain this distribution of hypotheses, such as, for example, Kalman filters and particle filters. It is also possible to record recent motions of the flexible device **100** and solve for the current roll angle using regression techniques such as non-linear least squares. Visually, this technique is shown in FIG. **13**.

As an example, a flexible device **100** with a single coil at the tip would allow all localization except for the roll axis. Moving the device (either manually or robotically) would cause both the EM sensor and elongation measurements to change, reflecting a change in position in each of their coordinate systems. Specifically, the EM sensor would have a new position and heading in the global coordinate system **610**, while the elongation measurements would reflect a new heading and orientation in the proximal device coordinate system **612**. If the device coordinate system was known in relation to the global coordinate system, the motion could be correlated between the two sensing modalities. For a given motion, there would be a specific roll angle that would be consistent with the motion. By combining multiple measurements over time, an estimator **606/506** could keep the roll angle updated, even as the roll angle changes as the flexible device **100** moves.

Multi-Coil Disturbance Rejection

The primary disturbances in EM tracker measurements are due to magnetic interference and electrical interference. Electrical interference causes noise in the measurements and often can be filtered out, but for faster motion, the elongation measurements could be used to provide higher frequency information than the EM tracker can provide on its own.

Another application for elongation measurements in conjunction with an EM tracker is in rejecting warping of the localization field due to changes in the magnetic field. Since EM trackers depend on magnetic fields in the area, and large bodies of ferromagnetic metal can warp this field, often the types of equipment in an operating room can disturb or change the localization as they move. For example, as a C-arm of a fluoroscopy system is rotated around a patient or moves closer or further from the patient, the magnetic field (and hence localization) is warped. By maintaining knowledge of elongation measurements, detection of the magnetic field being warped may be detected, even when the flexible device **100** is not moving. Thus localization field warping may be compensated for in software.

Localization with Maps and Elongation Measurements

As discussed above, elongation measurements can provide information about the deformation of a flexible medical device. If the device is operating in a region of the anatomy whose walls are sufficiently rigid so as to constrain the device, then a map of that anatomy can also provide information about the possible shapes the device may assume. The map may be obtained from pre-operative imaging, for example, from a CT scan; or intra-operatively, for example, from multiple views of contrast-enhanced 2D images or by collecting surface points using EM sensors. By correlating elongation measurements with shapes allowed by the anatomical map at different locations, an estimate of the shape of the device and its position within the map may be determined.

An example is use of elongation measurements are shown in FIG. **14**. More specifically, FIG. **14**A illustrates elongation measurements that continuously provide a 2 degree of freedom tip heading angle as a catheter **100** advances from time t_1 to t_4. FIG. **14**B illustrates a map of the vessel in which the catheter is navigating. By finding the best match between the measured heading angles over time in FIG. **14**A and the gradient of the center line of the map shown in FIG. **14**B, the current tip position within the anatomy can be determined, as illustrated in FIG. **14**C. Additionally, if the elongation measurements are noisy, imprecise, or reliable only within a plane, the shape estimate derived from the history of heading angles shown in FIG. **14**A can be improved based on the corresponding gradients of the center line of the map shown in FIG. **14**B.

It will be appreciated that the surgical instrument and methods described herein have broad applications. The foregoing embodiments were chosen and described in order to illustrate principles of the methods and apparatuses as well as some practical applications. The preceding description enables others skilled in the art to utilize methods and apparatuses in various embodiments and with various modifications as are suited to the particular use contemplated. In accordance with the provisions of the patent statutes, the principles and modes of operation of this disclosure have been explained and illustrated in exemplary embodiments.

It is intended that the scope of the present methods and apparatuses be defined by the following claims. However, it must be understood that this disclosure may be practiced otherwise than is specifically explained and illustrated without departing from its spirit or scope. It should be understood by those skilled in the art that various alternatives to the embodiments described herein may be employed in practicing the claims without departing from the spirit and scope as defined in the following claims. The scope of the disclosure should be determined, not with reference to the above description, but should instead be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. It is anticipated and intended that future developments will occur in the arts discussed herein, and that the disclosed systems and methods will be incorporated into such future examples. Furthermore, all terms used in the claims are intended to be given their broadest reasonable constructions and their ordinary meanings as understood by those skilled in the art unless an explicit indication to the contrary is made herein. In particular, use of the singular articles such as "a," "the," "said," etc. should be read to recite one or more of the indicated elements unless a claim recites an explicit limitation to the contrary. It is intended that the following claims define the scope of the invention and that the method and apparatus within the scope of these claims and their equivalents be covered thereby. In sum, it should be understood that the invention is capable of modification and variation and is limited only by the following claims.

What is claimed is:

1. A method of determining roll localization of a flexible elongate instrument as the flexible elongate instrument is navigated within a patient, wherein the flexible elongate instrument comprises at least one pullwire, the method comprising:

obtaining (i) an initial position or heading measurement for the flexible elongate instrument from at least a first sensor of a plurality of sensors;

obtaining (ii) a time history of measurements of motion in the at least one pullwire from at least a second sensor of the plurality of sensors as the flexible elongate instrument moves;

obtaining (iii) a time history of subsequent position or heading measurements from a remote localization system for the flexible elongate instrument as the flexible elongate instrument moves, the subsequent position or heading measurements being obtained from at least the first sensor of the plurality of sensors after the initial position or heading measurement; and

determining localization of a roll angle for the flexible elongate instrument from a comparison of (i) the initial position or heading measurement for the flexible elongate instrument, (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves, and (iii) the time history of the subsequent position or heading measurements from the remote localization system for the flexible elongate instrument as the flexible elongate instrument moves.

2. The method of claim **1**, wherein the first sensor includes a two-degree of freedom orientation sensor.

3. The method of claim **2**, wherein (i) the initial position or heading measurement for the flexible elongate instrument comprises measurements of pitch and yaw, and wherein (iii) the time history of the subsequent position or heading measurements from the remote localization system for the flexible elongate instrument as the flexible elongate instrument moves comprise comprises measurements of pitch and yaw.

4. The method of claim **1**, wherein the first sensor includes a five-degree of freedom sensor.

5. The method of claim **4**, wherein the five-degree of freedom sensor is an electromagnetic sensor.

6. The method of claim **1**, wherein said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves comprises receiving measurements of motion in multiple pullwires.

7. The method of claim **1**, wherein said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves is determined based on a time history of pullwire position commands.

8. The method of claim **1**, wherein said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves comprises receiving a measurement of pullwire displacement.

9. The method of claim **1**, wherein said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves comprises receiving a measure of tension changes in the at least one pullwire.

10. The method of claim **1**, wherein said determining localization of the roll angle for the flexible elongate instrument comprises determining a value that satisfies an optimization equation.

11. The method of claim **1**, wherein said determining localization of the roll angle for the flexible elongate instrument comprises maintaining and filtering multiple hypotheses over successive motions of the flexible elongate instrument.

12. The method of claim **11**, wherein the multiple hypotheses are maintained and filtered using one or more maintenance and filter options selected from the group consisting of Kalman filters, particle filters, and Gaussians combinations.

13. The method of claim **1**, wherein said determining localization of the roll angle for the flexible elongate instrument results in full localization of the flexible elongate instrument in six degrees of freedom.

14. The method of claim **1**, further comprising receiving an input command to move the flexible elongate instrument prior to said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves.

15. The method of claim **1**, wherein said obtaining (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves comprises predicting motion of the at least one pullwire based on an input command.

16. The method of claim **1**, further comprising predicting a movement of the flexible elongate instrument based on the

(ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves.

17. The method of claim 1, further comprising outputting the localization of the roll angle to a localization consumer.

18. A method of determining roll localization of a flexible elongate instrument as the flexible elongate instrument is navigated within a patient, wherein the flexible elongate instrument comprises at least one pullwire, the method comprising:

obtaining (i) an initial position or heading measurement for the flexible elongate instrument from at least a first sensor of a plurality of sensors;

obtaining (ii) a time history of measurements of motion in the at least one pullwire from at least a second sensor of the plurality of sensors as the flexible elongate instrument moves;

obtaining (iii) a time history of a plurality of subsequent position or heading measurements as the flexible elongate instrument moves, the plurality of subsequent position or heading measurements being obtained from at least the first sensor of the plurality of sensors after the initial position or heading measurement; and

determining localization of a roll angle for the flexible elongate instrument from a comparison of (i) the initial position or heading measurement for the flexible elongate instrument, (ii) the time history of the measurements of motion in the at least one pullwire as the flexible elongate instrument moves, and (iii) the time history of the plurality of subsequent position or heading measurements for the flexible elongate instrument as the flexible elongate instrument moves.

19. A method comprising:

obtaining (i) an initial position or heading measurement for a flexible elongate instrument from at least a first sensor of a plurality of sensors;

obtaining (ii) a time history of measurements of motion in one or more pullwires of the flexible elongate instrument from at least a second sensor of the plurality of sensors as the flexible elongate instrument moves within a patient;

obtaining (iii) a time history of a plurality of subsequent position or heading measurements as the flexible elongate instrument moves within the patient, the plurality of subsequent position or heading measurements being obtained from at least the first sensor of the plurality of sensors after the initial position or heading measurement; and

determining localization of a roll angle for the flexible elongate instrument from a comparison of (i) the initial position or heading measurement for the flexible elongate instrument, (ii) the time history of the measurements of motion in the one or more pullwires as the flexible elongate instrument moves within the patient, and (iii) the time history of the plurality of subsequent position or heading measurements for the flexible elongate instrument as the flexible elongate instrument moves within the patient.

* * * * *